

**T.C.
GEBZE TECHNICAL UNIVERSITY
GRADUATE SCHOOL**

**TURBOJET ENGINE STARTING PERFORMANCE
EVALUATION**

SENİH ÖZKAN

**A THESIS OF MASTER OF SCIENCE
DEPARTMENT OF ENERGY TECHNOLOGIES
APPLIED PROPULSION SYSTEM DESIGN AND
ENGINEERING FOR AEROSPACE TECHNOLOGIES
PROGRAM**

ADVISOR: ASSIST. PROF. DR. ALİ EKEN

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T.C.
GEBZE TEKNİK ÜNİVERSİTESİ
LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

TURBOJET MOTORU BAŞLATMA PERFORMANSI
DEĞERLENDİRMESİ

SENİH ÖZKAN

YÜKSEK LİSANS TEZİ
ENERJİ TEKNOLOJİLERİ ANABİLİM DALI
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*To my family and
my fiancée*

ABSTRACT

The successful starting of a turbojet engine, particularly in the early development phases, depends significantly on the selection of the starter system and the management of surge margin. This study investigates the combined effects of starter sizing and bleed air scheduling on compressor surge behavior and engine starting performance.

A physics-based simulation model was developed using scaled turbomachinery maps extended to sub-idle conditions by applying zero-speed interpolation techniques. Instead of conventional efficiency-based performance maps, torque-based maps were employed to capture low-speed dynamics more accurately. Sixteen different start scenarios were analyzed by combining four different starter torque capacities with four different surge bleed schedules.

Results show that selecting a more powerful starter significantly reduces engine starting time and modestly increases the surge margin. However, this also results in increased weight and volume, which are critical drawbacks in aerospace applications. On the other hand, increasing the amount of bleed air extracted from the compressor outlet during starting greatly improves surge margin by reducing the compressor pressure ratio, moving the operating point away from the surge line. Nevertheless, this strategy leads to an increase in turbine inlet temperature (TIT), which may cause thermal risks during prolonged start sequences.

Among the sixteen cases studied, six combinations maintain the compressor surge margin above the 10% safety threshold throughout the start sequence. However, five of these six cases exceed the 900 K starting exhaust gas temperature (EGT) limit. Consequently, a final selection of a starter and handling bleed schedule is made, balancing surge protection, thermal limits, starter weight considerations and starting time requirements.

This study contributes valuable insight for engine designers seeking optimal starter and bleed configurations during the conceptual phase, ensuring reliable starts without compromising safety or exceeding platform constraints.

Keywords: Starter, Handling Bleed, Surge, Starting, Control, Sub-Idle

ÖZET

Turbojet motorunun başarıyla çalıştırılması, özellikle erken geliştirme aşamalarında, büyük ölçüde başlatıcı (starter) sisteminin seçimine ve kompresör kararsızlık (surge) marjının yönetimine bağlıdır. Bu çalışma, motor başlatıcı boyutlandırmasının ve bleed hava zamanlamasının kompresör kararsızlık davranışı ve motor çalıştırma performansı üzerindeki birleşik etkilerini incelemektedir.

Fizik tabanlı bir benzetim modeli, sıfır hız interpolasyon tekniklerinden yararlanılarak rölanti altı koşullara genişletilmiş ölçeklenmiş turbomakine haritaları kullanılarak geliştirilmiştir. Geleneksel verimlilik temelli performans haritaları yerine, düşük hız dinamiklerini daha doğru yakalamak amacıyla tork tabanlı turbomakine haritaları kullanılmıştır. Dört farklı başlatıcı tork kapasitesi ile dört farklı kompresör kararsızlık bleed zamanlamasının kombinasyonu oluşturularak toplam on altı farklı çalıştırma senaryosu analiz edilmiştir.

Sonuçlar, daha güçlü bir starter seçiminin motorun hızlanma süresini önemli ölçüde azalttığını ve kompresör kararsızlık marjını sınırlı ölçüde artırdığını göstermektedir. Ancak, bu aynı zamanda ağırlık ve hacimde artışa yol açmakta olup, bu durum havacılık uygulamalarında kritik bir dezavantaj teşkil etmektedir. Öte yandan, çalıştırma sırasında kompresör çıkışından çekilen bleed hava miktarının artırılması, kompresör basınç oranını düşürerek çalışma noktasını kompresör kararsızlık hattından uzaklaştırmakta ve böylece kompresör kararsızlık marjını büyük ölçüde iyileştirmektedir. Ancak bu strateji, türbin giriş sıcaklığında artışa yol açmakta ve uzun süreli başlatma sekanslarında termal riskler doğurabilmektedir.

İncelenen on altı durum arasında, altı kombinasyon başlatma dizisi boyunca kompresör kararsızlık marjını %10 güvenlik eşiğinin üzerinde tutmaktadır. Bununla birlikte, bu altı durumdan beşi 900 K'lık başlatma egzoz gaz sıcaklığı limitini aşmaktadır. Netice olarak, kompresör kararsızlık koruması, termal sınırlar, başlatıcı ağırlığı ve motor başlatma süresi gereksinimleri dikkate alınarak nihai bir başlatıcı ve kompresör kararsızlık bleed planı seçilmektedir.

Bu çalışma, kavramsal tasarım aşamasında güvenilir çalıştırmayı sağlarken güvenlikten ödün vermeyen ve platform kısıtlarını aşmayan optimal başlatıcı ve bleed konfigürasyonlarını arayan motor tasarımcılarına değerli bir bakış açısı sunmaktadır.

Anahtar Kelimeler: Başlatıcı, İşletme Havası, Kompresör Kararsızlığı, Başlatma, Kontrol, Rölanti Altı

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LIST OF SYMBOLS AND ABBREVIATIONS

A	: Nozzle exit area
c_p	: Specific heat at constant pressure
c_v	: Specific heat at constant volume
F	: Thrust
I	: Shaft moment of inertia
k_{PR}	: Compressor 0-speed line coefficient
$\dot{m}$	: Mass flow rate
$\dot{m}_c$	: Corrected mass flow rate
M	: Mach number
N	: Rotational speed
P	: Pressure
P_o	: Ambient static pressure
P_{s3}	: Compressor exit static pressure
P_t	: Total (stagnation) pressure
π	: Pressure ratio
s	: Specific entropy
T	: Temperature
T_o	: Ambient static temperature
T_t	: Total (stagnation) temperature
V	: Velocity
W	: Power
γ	: Ratio of specific heats (c_p/c_v)
η	: Efficiency
η_b	: Combustion efficiency
η_c	: Burner isentropic efficiency
η_t	: Turbine isentropic efficiency
η_{mech}	: Mechanical efficiency
Ω	: Burner loading parameter
τ	: Torque
ω	: Angular speed
$\dot{\omega}$	: Angular acceleration
β	: Beta line parameter in compressor map
δ	: Normalized pressure parameter
APU	: Auxiliary Power Unit
ATS	: Air Turbine Starter
CFD	: Computational Fluid Dynamics
EGT	: Exhaust Gas Temperature
FADEC	: Full Authority Digital Engine Control
FAR	: Fuel-to-Air Ratio
GSU	: Ground Support Unit
HP	: High Pressure
IP	: Intermediate Pressure
LHV	: Lower Heating Value
LP	: Low Pressure
ISA	: International Standard Atmosphere
NDOT	: Time derivative of shaft speed
NGV	: Nozzle Guide Vane

NPSS	: Numerical Propulsion System Simulation
PI	: Proportional-Integral
PR	: Pressure Ratio
SFC	: Specific Fuel Consumption
SLS	: Sea Level Static
TIT	: Turbine Inlet Temperature
VIGV	: Variable Inlet Guide Vane
VSV	: Variable Stator Vane
K	: Kelvin
kg	: Kilogram
kN	: Kilonewton
kPa	: Kilopascal
kW	: Kilowatt
m	: Meter
rpm	: Revolutions per minute
s	: Second



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1. INTRODUCTION

Gas turbine engines are widely used in aviation and power generation due to their high power-to-weight ratio and efficiency. The starting process of these engines is a critical phase that directly affects their reliability and operational efficiency. Although the starting phase of gas turbine engines typically occurs over a period of 30 to 120 seconds, it continues to be a topic of significant interest due to the high level of uncertainty and complexity involved. Among the various challenges encountered during the starting process, compressor surge is arguably the most critical and uncertain phenomenon.

In modern engines, the two most commonly employed methods to protect the compressor from surge are Variable Stator Vanes (VSVs)/Variable Inlet Guide Vanes (VIGVs), and handling bleed valves. As illustrated in **Figure 1.1** [1], VSVs modify the compressor map by changing the incidence angle of the airflow approaching the compressor blades at specific operating points, thereby shifting the operating line away from the surge line.

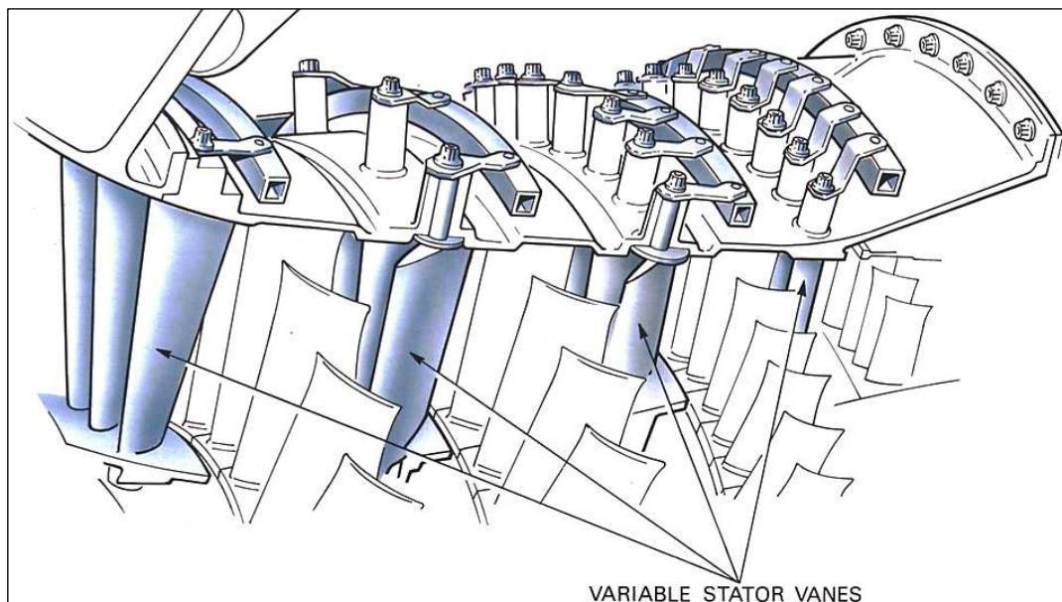


Figure 1.1: Compressor variable stator vanes

Handling bleed valves, shown in **Figure 1.2**, enable air to be extracted either from intermediate compressor stages or directly from the compressor exit. By extracting air,

the compressor pressure ratio is reduced, allowing the operating point to move away from the surge line without altering the compressor map.

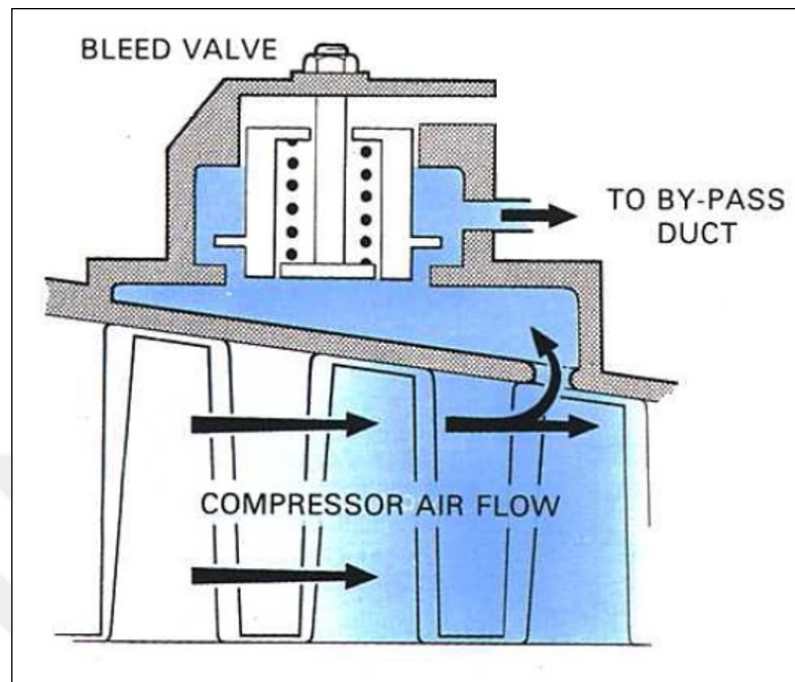


Figure 1.2: Handling bleed valve

In principle, the use of a more powerful starter also shifts the compressor operating point slightly away from surge. However, increasing starter power inevitably leads to an increase in engine and, consequently, aircraft weight, making this approach a clear trade-off.

The objective of this thesis is to optimize the engine starting performance by determining a safe and requirement-compliant starter power and handling bleed schedule that prevent the compressor from exceeding surge limits during the starting process of a turbojet engine. In making these selections, three key parameters are considered: exhaust gas temperature (EGT), compressor surge margin and engine starting time.

The Brayton cycle, commonly referred to as the gas turbine cycle, forms the fundamental thermodynamic basis for the operation of modern turbojet and turbofan engines. The cycle consists of isentropic compression in the compressor, constant-pressure heat addition in the combustion chamber, isentropic expansion in the turbine, and the discharge of working gases to the atmosphere. In practical engines, deviations

from this ideal cycle occur due to factors such as component inefficiencies, pressure losses, and non-ideal combustion.

Figure 1.3 illustrates the ideal Brayton cycle on a temperature–entropy (T – s) diagram. Compression and expansion processes appear nearly vertical due to their approximately isentropic nature, while heat addition and exhaust occur at nearly constant pressure, represented by horizontal lines in the diagram. This visualization highlights the energy transformations within the cycle and provides a clear view of work input, work output, and thermal efficiency.

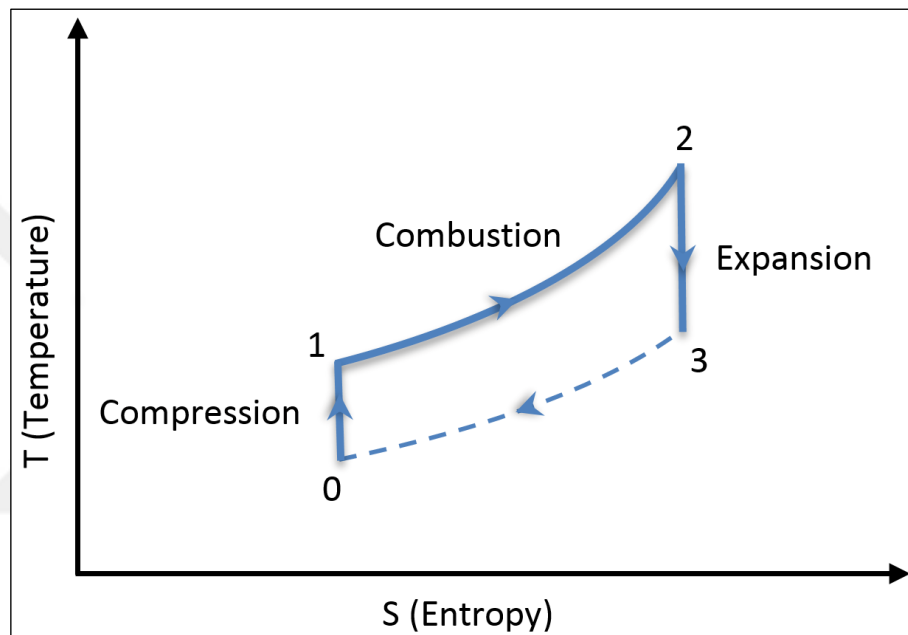


Figure 1.3: Ideal brayton cycle on a temperature–entropy diagram

Gas turbine engines operate on the principle of continuous air intake, compression, combustion, and expansion through turbines. Among the various types of gas turbines, turbojet engines are primarily used in high-speed aircraft due to their simplicity and high thrust production. A turbojet engine consists of an inlet, compressor, combustion chamber, turbine, duct and exhaust nozzle. A single spool turbojet engine and its components are shown in **Figure 1.4**.

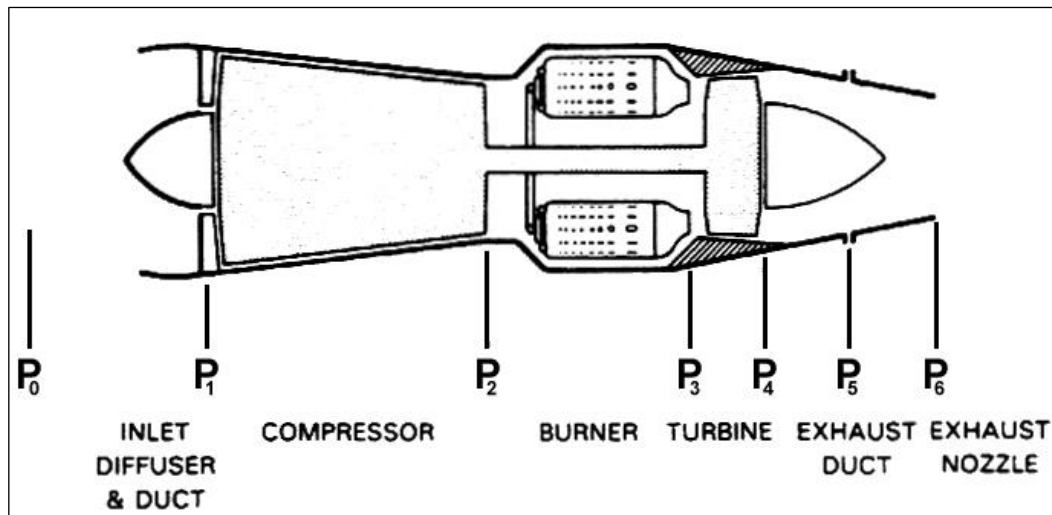


Figure 1.4: A single spool turbojet engine

To initiate the starting process, an external power source is required to rotate the engine until it reaches a self-sustaining speed. The air turbine starter (ATS) is a common solution for this purpose. It operates by converting compressed air energy into mechanical rotational energy, driving the engine's high-pressure spool during starting. A schematic representation of how an ATS starts the main engine is shown in **Figure 1.5**. The ATS can be operated using cross-bleed air from a running engine, air from the Auxiliary Power Unit (APU), or air supplied by Ground Support Unit (GSU). A cutaway view of the ATS is presented in **Figure 1.6**.

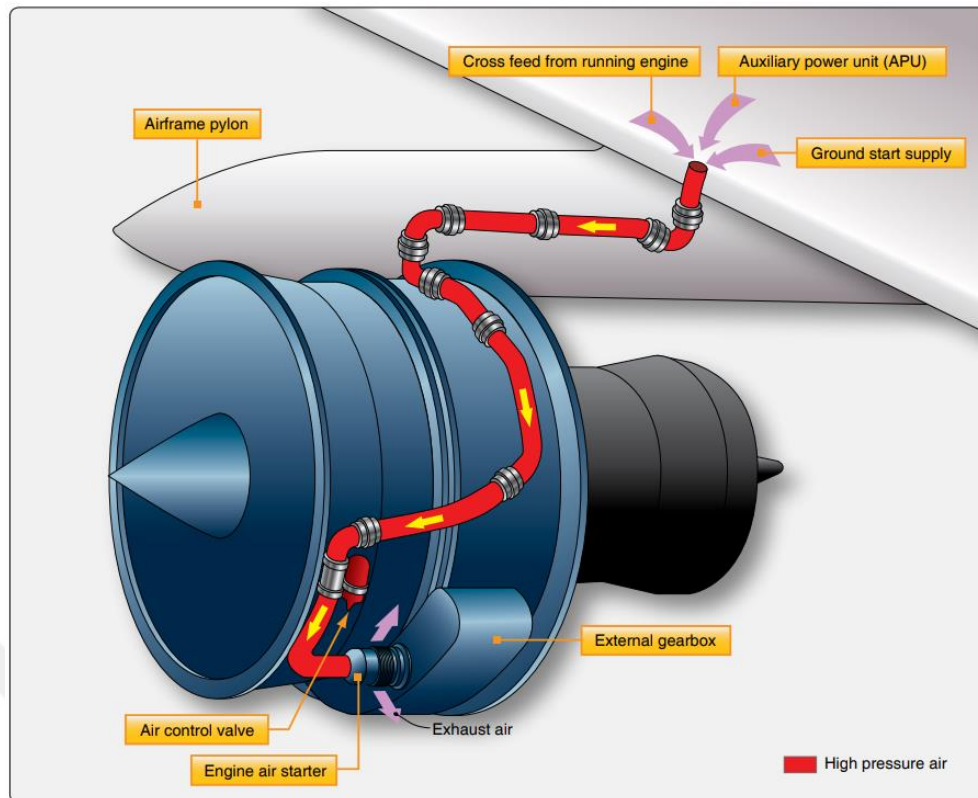


Figure 1.5: A schematic representation of how an ATS starts the main engine

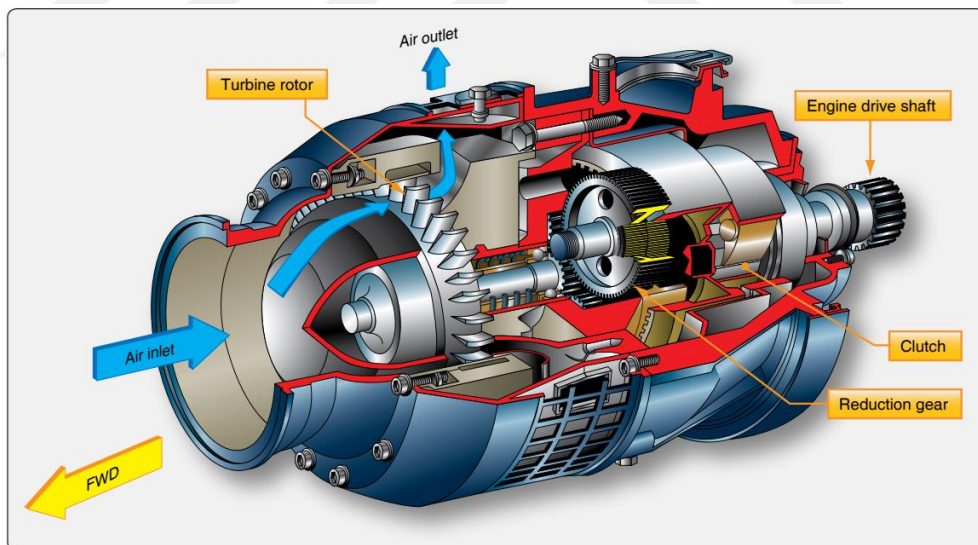


Figure 1.6: A cutaway view of the ATS

The starting sequence of a gas turbine engine is a delicate operation that requires precise control of airflow, fuel scheduling, and ignition timing. A successful starting ensures that the engine reaches stable operation within a safe temperature and pressure range. Failure to properly manage the starting process can lead to excessive wear,

component damage, or even engine failure. Therefore, understanding and optimizing starting dynamics is crucial for the reliability and longevity of gas turbine engines.

Before conducting physical tests, predicting the starting characteristics of a gas turbine engine through simulations provides significant advantages in the design phase. It helps engineers refine control strategies, assess component performance, and identify potential failure points early in the development cycle. By simulating different starting scenarios, designers can ensure that the engine will operate safely and efficiently under varying conditions, reducing the need for costly and time-consuming experimental tests.

The selection of a suitable starter and auxiliary power unit (APU) is a key design consideration for gas turbine engines. The choice of starter impacts the engine's ability to reach self-sustaining speeds efficiently and safely. Similarly, the APU, which provides compressed air and electrical power during starting, must be properly sized to meet the engine's requirements. Understanding the starting process enables engineers to select the most suitable starter and APU configuration, ensuring optimal engine performance and operational reliability.

This thesis will explore these aspects in detail, providing a comprehensive analysis of turbojet engine starting dynamics and their implications for engine design and operation.

2. LITERATURE STUDY

This section reviews the literature relevant to the main research topics addressed in this thesis. Since the present study focuses on the starting process of a turbojet engine, the reviewed literature primarily covers sub-idle performance modeling of turbomachinery components, approaches for modeling engine start, associated modeling challenges, computational tools, starting control strategies, and related studies reported in the open literature.

Accurate representation of turbomachinery behavior under sub-idle operating conditions is essential for reliable engine starting simulations. However, experimental data in this regime are extremely limited, making the derivation and extrapolation of compressor and turbine performance maps at low rotational speeds a persistent challenge. Consequently, numerous methodologies have been proposed to extend turbomachinery maps into the sub-idle region, particularly for engine starting and transient analyses.

The modeling of gas turbine engine starting performance is widely recognized as one of the most challenging aspects of engine simulation, especially during the conceptual design and early development phases [2, 3, 4]. Unlike steady-state or high-speed operation, the starting phase involves very low rotational speeds, strong transient effects, and pronounced coupling between engine components. During this phase, the engine operates predominantly in the sub-idle regime, where reliable experimental component data are scarce. As a result, accurate modeling often relies on costly full-engine testing, motivating extensive research into theoretical and empirical methods for extending conventional turbomachinery maps down to zero rotational speed [5, 6, 7, 8].

Early studies on sub-idle operation were largely based on similarity principles derived from incompressible flow theory to estimate engine operating lines during starting. The generalized framework introduced by Agrawal and Yunis [9] provided one of the earliest systematic approaches for predicting starting characteristics. Later studies incorporated compressibility effects, improving prediction accuracy in the speed range between ignition and idle [10, 11, 12]. While these works provided valuable insight into low-speed behavior, they also highlighted fundamental limitations of

conventional performance parameters under highly unsteady and extremely low-speed conditions typical of engine start and windmilling.

One of the most critical issues identified in the literature concerns the use of compressor isentropic efficiency in the sub-idle regime. As rotational speed approaches zero, the compressor pressure ratio tends toward unity and the temperature rise becomes negligible, rendering the efficiency definition mathematically ill-conditioned. This behavior leads to numerical instability and physically meaningless results, significantly degrading the robustness and convergence of transient starting simulations based on efficiency-driven formulations [7, 8, 13].

To overcome these limitations, several studies have proposed alternative performance parameters that remain well-defined at low rotational speeds. Riegler et al. [13] showed that specific torque or specific work provides a more suitable basis for low-speed compressor modeling, as torque remains finite even at zero rotational speed, corresponding to the locked-rotor condition. This property enables a continuous and numerically stable representation of turbomachinery behavior throughout the entire starting and windmilling sequence.

Building on this foundation, subsequent studies reformulated conventional performance solvers into torque-based frameworks. Grech [6] developed a comprehensive sub-idle modeling methodology in which efficiency-based turbomachinery maps were transformed into torque-based representations and validated against experimental data. Extending earlier work by Zachos [8], these studies demonstrated that torque-based models significantly improve numerical robustness and reduce convergence difficulties under low speed operating conditions such as ground start and altitude relight.

A critical requirement for torque-based modeling is the reliable extension of turbomachinery maps from normal operating conditions down to zero rotational speed. Due to the lack of experimental data at very low speeds, this process relies on appropriate extrapolation and interpolation techniques. Kurzke [5, 14, 15, 16] proposed several map extension strategies based on incompressible flow assumptions with compressibility corrections, demonstrating that near-linear relationships between corrected specific torque and corrected mass flow rate can be used effectively without detailed turbomachinery geometry information.

Complementary studies emphasized the importance of incorporating empirical data from locked-rotor and windmilling tests into the map extension process. Interpolation methods anchored to such reference data were shown to produce more realistic trends and improved accuracy—particularly under windmilling conditions—than purely mathematical extrapolation from higher-speed data [11, 17, 18]. High-fidelity restart and acceleration simulations further highlighted the sensitivity of sub-idle predictions to both map extension methodology and numerical formulation [19].

Overall, the literature indicates a clear consensus that reliable sub-idle performance modeling requires physically consistent map extension and the use of performance parameters that remain well-behaved across the entire low-speed operating range [6, 7, 8, 16]. Torque-based modeling combined with zero-speed map extension has therefore become essential for achieving numerical stability and realistic component behavior during transient engine starting simulations. Accordingly, the present thesis adopts this physics-based approach to investigate the combined effects of starter sizing and handling bleed air scheduling on compressor surge behavior during turbojet engine starting.

Güllü et al. [20] employed the standard turbojet engine model available in GasTurb to investigate the sensitivity of starting simulations. Their results showed that turbomachinery torque characteristics and turbine capacity are the dominant parameters governing accurate model calibration for this type of engine architecture.

In the engine starting literature, starter power and handling bleed management have generally been investigated separately. Grech [6] examined the influence of different starter power levels on sub-idle engine performance, focusing on acceleration toward self-sustaining operation. In other study, Sexton [12] investigated the effects of handling bleed schedules, demonstrating that appropriate bleed management can control turbine inlet temperature while maintaining adequate compressor surge margin during starting.

Despite these contributions, limited attention has been given to the combined influence of starter power and handling bleed scheduling. A systematic sensitivity analysis considering both parameters simultaneously has not been reported in the open literature. The present study addresses this gap by examining how variations in starter

power level and handling bleed scheduling jointly affect engine starting performance, providing a more integrated understanding of the starting operating envelope.

In this thesis, GasTurb [21], NPSS [22], Smooth C–T [23, 24], and MATLAB/Simulink [25] are used within an integrated modeling framework to analyze turbojet engine starting and sub-idle behavior. GasTurb is employed to obtain steady-state performance using a zero-dimensional component-matching approach, while the same engine model is independently implemented in NPSS to enable more accurate modeling of the sub-idle regime and to allow coupling with Simulink for transient performance analysis. Compressor and turbine maps are processed using Smooth C and Smooth T to ensure numerical smoothness in the above-idle regions, while sub-idle maps are generated using an in-house MATLAB-based tool. The complete model is finally implemented in MATLAB/Simulink to perform time-dependent simulations and evaluate starting control strategies [25, 26].

In summary, the reviewed literature highlights the importance of physically consistent sub-idle modeling and reliable turbomachinery map extension for accurate engine starting simulations. While many aspects of the starting process have been studied, integrated investigations addressing the combined effects of starter power and bleed scheduling remain limited. The present thesis builds on established approaches to contribute to a more comprehensive understanding of turbojet engine starting behavior.

3. THEORY AND MODELLING

In this study, the default single-spool turbojet engine model available in GasTurb [21] is utilized. At the design point (SLS, ISA conditions), the engine produces approximately 26.4 kN of thrust. The compressor inlet mass flow rate is 32 kg/s, and the compressor pressure ratio is 12. The shaft rotational speed is 14284 rpm, and the turbine inlet temperature is 1450 K. The shaft moment of inertia is 5.23 kg·m².

A total of 10% bleed air is extracted from the compressor, with 5% used for NGV cooling and 5% for turbine blade cooling. The turbojet secondary air system and station numbering are shown in **Figure 3.1**.

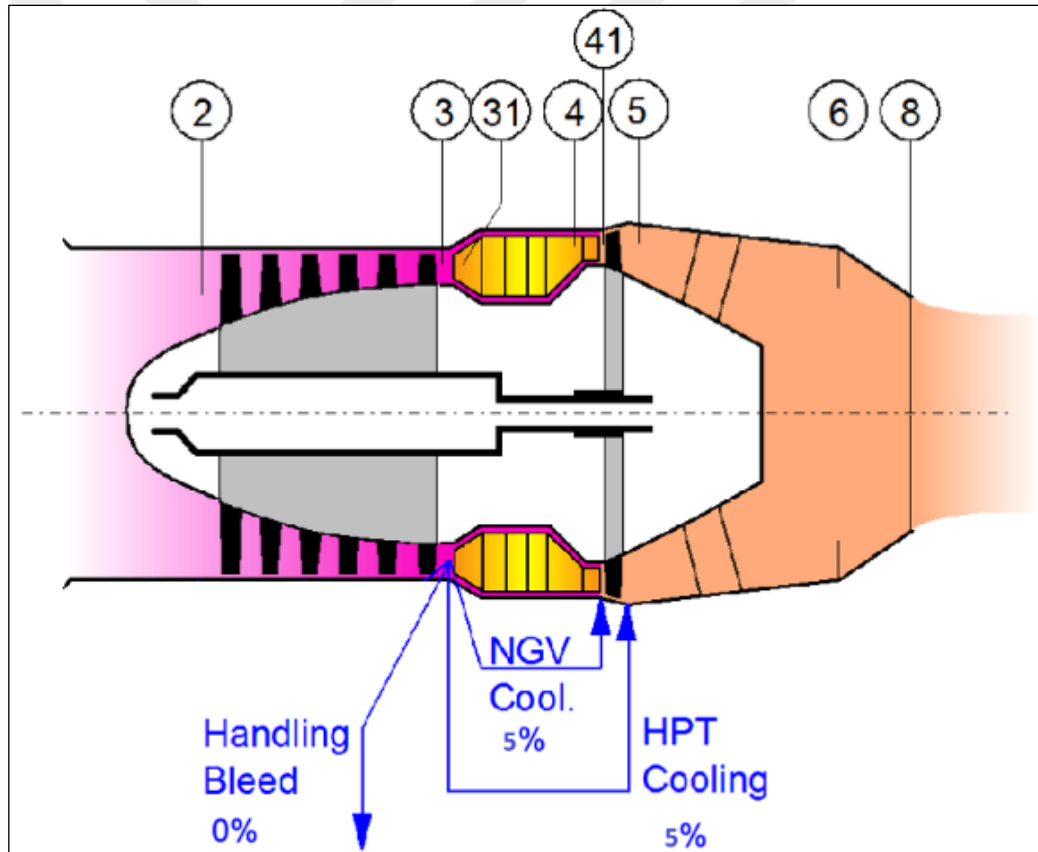


Figure 3.1: Single spool turbojet engine air system in GasTurb [6].

The thermodynamic station names of a single spool turbojet engine are given in **Table 3.1**.

Table 3.1: Thermodynamic station names

Station Number	Definition
0	Ambient
1	Aircraft - Engine Interface
2	Compressor Inlet
3	Compressor Outlet
31	Burner Inlet
4	Burner Outlet
41	Turbine NGV Outlet/Rotor Inlet
49	Turbine Outlet
5	Duct Inlet
6	Nozzle Inlet
8	Nozzle Outlet

3.1. Thermodynamic Model

The turbojet engine is modeled based on its thermodynamic cycle, following a real (non-ideal) Brayton cycle. Unlike the ideal cycle, the real Brayton cycle accounts for component inefficiencies, pressure losses, and non-ideal behavior of the compressor, turbine, and burner. The real Brayton cycle T-s diagram is shown by the blue line in **Figure 3.2**. The model calculates total (stagnation) temperature and pressure at each component, which serve as intermediate variables for performance evaluation. Ultimately, the main objective of the model is to determine the engine thrust, which is obtained by converting the thermal and pressure energy of the exhaust gases into kinetic energy in the nozzle.

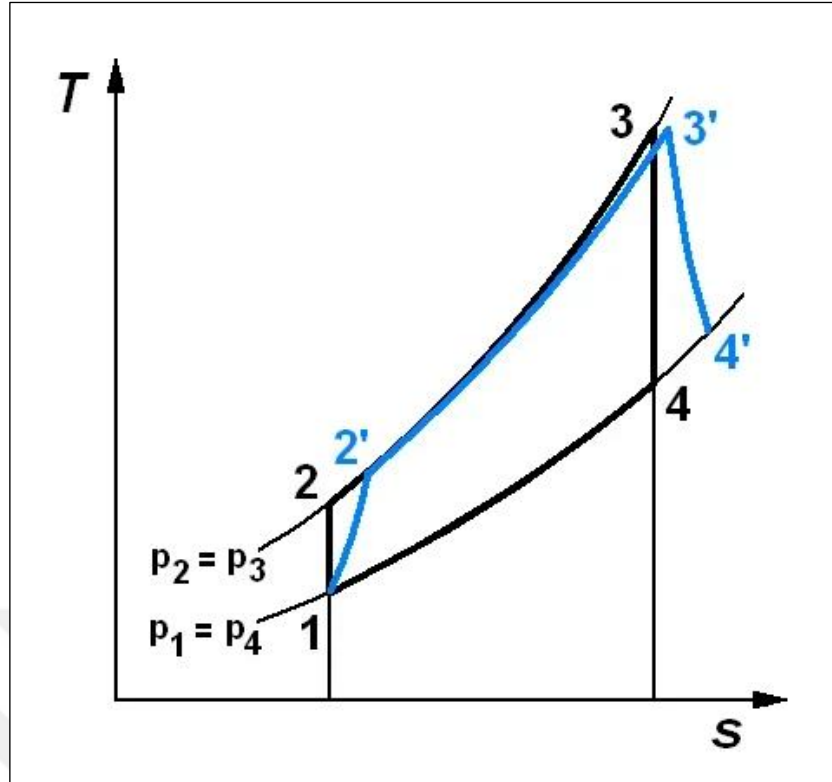


Figure 3.2: Real (blue) vs ideal (black) brayton cycles

The structure of a typical single-spool turbojet engine model in GasTurb and NPSS is shown in **Figure 3.3**. The main components used are the ambient, inlet, compressor, burner, turbine, nozzle, and shaft, and these components are briefly described in the following sections.

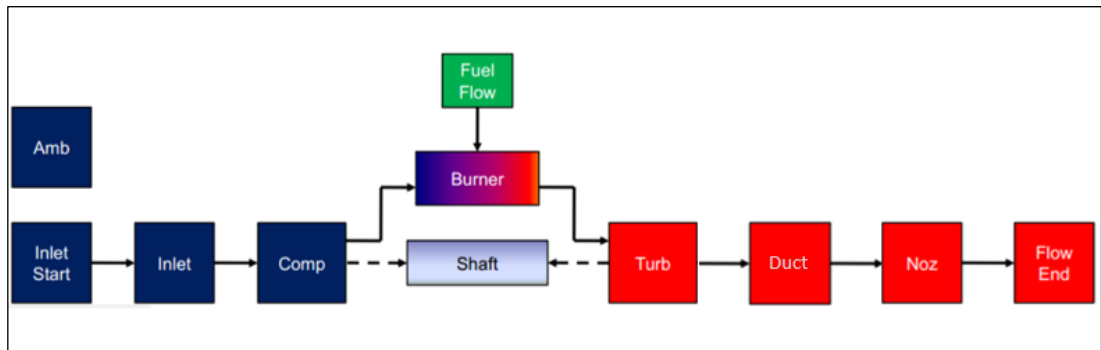


Figure 3.3: Single spool turbojet engine model structure

3.1.1. Ambient (Freestream Conditions)

The ambient conditions define the initial properties of the air entering the engine, including temperature and pressure. These properties are assumed uniform and static at a given altitude, serving as the baseline for all subsequent calculations. Total

(stagnation) conditions at the inlet are calculated using the freestream Mach number and ambient properties.

Ambient temperature:

$$T_{amb} = T_{\infty} \quad (3.1)$$

Ambient pressure:

$$P_{amb} = P_{\infty} \quad (3.2)$$

Engine inlet total pressure:

$$P_{t1} = P_{amb} \left(1 + \frac{\gamma-1}{2} M_{\infty}^2 \right)^{\frac{\gamma}{\gamma-1}} \quad (3.3)$$

Engine inlet total temperature:

$$T_{t1} = T_{amb} \left(1 + \frac{\gamma-1}{2} M_{\infty}^2 \right) \quad (3.4)$$

3.1.2. Inlet

The inlet directs freestream air to the compressor while minimizing pressure losses. For subsonic inlets, it is assumed that no significant heat transfer occurs and that the deceleration of the flow does not change the total temperature. A small pressure loss is included to account for friction and minor geometric losses.

Outlet temperature:

$$T_{t2} = T_{t1} \quad (3.5)$$

Outlet pressure:

$$P_{t2} = P_{t1} * \pi_i \quad (3.6)$$

3.1.3. Compressor

The compressor increases the pressure of the incoming air to provide the required conditions for combustion. Real compressors exhibit mechanical losses and flow irreversibilities; therefore, the actual compression deviates from an ideal isentropic process. This deviation is captured using the compressor isentropic efficiency η_c .

The pressure ratio π_c is taken from the compressor performance map or design specifications, and the outlet total pressure is directly determined by this ratio. The outlet total temperature is calculated by first evaluating the ideal (isentropic) temperature rise and then correcting it using the efficiency definition.

Ideal (isentropic) outlet temperature:

$$T_{t3_{ideal}} = T_{t2} \left(\pi_c^{\frac{\gamma-1}{\gamma}} \right) \quad (3.7)$$

Actual outlet temperature:

$$T_{t3} = T_{t2} + \frac{T_{t3_{ideal}} - T_{t2}}{\eta_c} \quad (3.8)$$

Outlet pressure:

$$P_{t3} = P_{t2} * \pi_c \quad (3.9)$$

3.1.4. Burner

The burner injects fuel into the compressed air and raises its energy content through combustion, which is assumed to occur at approximately constant pressure. A small pressure drop is included to account for friction and losses within the combustor. Combustion efficiency is less than one to reflect incomplete fuel burning, and the fuel-to-air ratio is chosen to achieve the desired exit temperature.

Outlet temperature:

$$T_{t4} = T_{t3} + \frac{f_{ar} * LHV * \eta_b}{c_p(1 + f_{ar})} \quad (3.10)$$

Outlet pressure:

$$P_{t4} = P_{t3} * \pi_b \quad (3.11)$$

3.1.5. Turbine

The turbine converts part of the thermal energy of the high-temperature gases into mechanical work, which is used to power the compressor and the associated engine accessories. The expansion is assumed adiabatic, but non-ideal behavior is represented via the turbine isentropic efficiency η_t . The turbine work is matched to the compressor work to satisfy shaft power balance.

Ideal (isentropic) outlet temperature:

$$T_{t5_{ideal}} = T_{t4} \left(\pi_t^{\frac{-\gamma+1}{\gamma}} \right) \quad (3.12)$$

Actual outlet temperature:

$$T_{t5} = T_{t4} - \eta_t (T_{t4} - T_{t5_{ideal}}) \quad (3.13)$$

Outlet pressure:

$$P_{t5} = P_{t4} * \pi_t \quad (3.14)$$

3.1.6. Nozzle

The nozzle converts the remaining thermal and pressure energy into kinetic energy, producing thrust. The expansion is assumed adiabatic. Exit velocity is found from the drop in total-to-static temperature, and thrust is computed from the momentum and pressure differences.

Static temperature at nozzle exit:

$$T_e = T_{t5} \left(\frac{P_e}{P_{t5}} \right)^{\frac{\gamma-1}{\gamma}} \quad (3.15)$$

Exit velocity:

$$V_e = \sqrt{2c_p(T_{t5} - T_e)} \quad (3.16)$$

Thrust:

$$F = \dot{m}(V_e - V_0) + A(P_e - P_0) \quad (3.17)$$

3.1.7. Shaft

A rotating element that mechanically connects the compressor and turbine, transmitting the power produced in the turbine to the compressor. The power generated in the turbine is transmitted through the shaft; however, this transfer is not fully efficient due to friction and viscous losses in bearings and the lubrication system. The mechanical efficiency is usually expressed as:

$$\eta_{mech} = \frac{W_{comp}}{W_{turb}} \quad (3.18)$$

Here, W_{turb} represents the mechanical power generated by the turbine, and W_{comp} is the power required by the compressor. The mechanical efficiency is less than 1 and typically ranges between 97–99%. The shaft is designed to minimize losses, with high rigidity, proper alignment, low-friction bearings, and effective lubrication.

3.2. Steady-State Model

Ensuring accurate steady-state conditions in turbojet engine analysis is essential for both model validation and the reliability of subsequent transient simulations. Steady-state refers to an operating condition in which shaft speed, mass flow rates, temperatures, and pressures remain constant over time, and the compressor and turbine torques are in perfect balance. In a single-spool turbojet model, steady-state matching is achieved by aligning the compressor and turbine maps at the same shaft speed in terms of mass flow and pressure ratio, satisfying the energy balance within the combustor, and ultimately ensuring that the turbine torque exactly matches the

compressor torque. For a given shaft speed, the mass flow and pressure ratio obtained from the compressor map are iteratively reconciled with the fuel flow determined from the combustor energy balance and the corresponding turbine map values. To solve these nonlinear relationships efficiently, engine simulation environments such as NPSS typically employ Newton–Raphson–based solvers, which simultaneously resolve the system of equations governing mass, energy, and torque balance. This method rapidly reduces residual errors and significantly accelerates convergence toward a stable operating point. Once mass flow continuity and torque equilibrium are achieved across all components, the solution is identified as a steady-state point. A robust steady-state matching methodology, coupled with an effective solver, forms the foundation for accurate off-design performance predictions as well as reliable modeling of transient processes such as starting, acceleration, and deceleration of the engine.

A steady-state model is developed in NPSS using the design point component parameters from the standard Turbojet model in GasTurb. Subsequently, to obtain results at off-design operating points, the turbomachinery maps and the off-design characteristics of the other components are incorporated.

3.2.1. Design Point

The design point is the reference operating condition at which a turbojet engine is optimized to achieve maximum efficiency. At this condition, component matching between the compressor, turbine, and other engine elements is established, and key performance parameters, such as mass flow rate, pressure ratio, temperature levels, and component efficiencies, are determined. All corrections, map scalings, and performance predictions used in off-design analyses are derived from the values obtained at the design point. In this regard, the design point serves as a critical reference for both steady-state and transient performance calculations.

For the standard turbojet engine in GasTurb, the design point is selected at SLS ISA condition. The component parameters at the design point for this turbojet engine are presented in **Table 3.2**.

Table 3.2: Turbojet engine design point parameters

Ambient	
Altitude, m	0
Mach	0
T_{ambient} , °C	15
P_{ambient} , kPa	101.325
Inlet	
PR	0.99
W, kg/s	31.68
Compressor	
PR	12
$\eta_{\text{compressor}}$	0.85
Burner	
PR	0.97
LHV, kJ/kg	43124
η_{burner}	0.9999
Turbine	
PR	3.178
η_{turbine}	0.89
Duct	
PR	0.98
Nozzle	
CD	1
CFG	1
Shaft	
HPX, kW	0
$\eta_{\text{mechanical}}$	0.9999
Bleed	
NGV, %W2	5
Rotor, %W2	5

The comparison of the design-point results obtained from the steady-state model developed in NPSS and the GasTurb model is presented in 4.1.

3.2.2. Off-Design Points

Off-design points refer to all operating conditions in which an engine operates outside its design point. These points are used to evaluate the engine's performance, efficiency, and operational limits under off-design conditions.

Three different points are selected to validate the NPSS steady-state model at off-design conditions. In choosing these points, attention is paid to varying PLA settings, different power demands, and different atmospheric conditions. These three points are as follows:

1. SLS ISA+30°C without power extraction,
2. 500 kW of extracted power at SLS ISA,
3. 70% shaft speed at SLS ISA without power extraction.

The comparison results will be presented in 4.2.

3.3. Transient Model

Transient refers to the time-dependent behavior of a system when it moves from one operating condition to another, such as during engine start, acceleration, deceleration, or throttle changes. For a turbojet engine, a transient model is important because it allows the prediction of time-dependent variables such as shaft speeds, temperatures, pressures, and thrust, which cannot be captured by steady-state models.

Transient analyses are essential to ensure safe and efficient operation during dynamic events, to prevent exceedance of temperature or stress limits, and to evaluate starting performance, spool acceleration, and response to control inputs.

In transient conditions, the variation of spool speed in a turbojet engine is determined using the net torque method. In this approach, the torque required by the compressor and the torque produced by the turbine are calculated separately, and the difference between them dictates the acceleration of the spool.

The net torque on the shaft is defined as:

$$\tau_{net} = \tau_{turbine} - \tau_{compressor} - \tau_{accessories} \quad (3.19)$$

This net torque determines the angular acceleration of the spool according to:

$$\tau_{net} = I\dot{\omega} \quad (3.20)$$

Where I denotes the shaft's moment of inertia and $\dot{\omega}$ represents the rate of change of angular speed.

The sign of the net torque determines the dynamic behavior of the spool. A positive net torque produces acceleration, while a negative net torque leads to deceleration. This formulation enables accurate time-domain modeling of engine behavior during starting, acceleration, deceleration, and response to control inputs.

To run NPSS and Simulink models together, an S-function block is available within Simulink. By preparing a config file that serves as the interface between NPSS and Simulink, the NPSS model can be easily connected to Simulink. The config file defines the NPSS model to be executed by Simulink, as well as the inputs and outputs of the Simulink S-function block. As an example, the input and output parameters of a sample config file are presented in **Figure 3.4**.

```
commandLine = "-I. ../check\\Turbojet_transient.run";

SimulinkInPortMapper inPort0 {
vars = { "BrnPri.Wfuel","ShH.HPX"} // Inputs of S-function block
}
SimulinkOutPortMapper outPort0 {
vars = { "ShH.Nmech","TrbH.Fl_I.Tt"} // Outputs of S-function block
}
states = { "ShH.Nmech"};
initialValues = {71.4}; // Initial value of transient analysis
derivatives = { "ShH.dNgdt"};
```

Figure 3.4: Sample config file

As shown in **Figure 3.4**, the Turbojet_transient.run (NPSS turbojet engine model) file in the "check" folder is executed. In this example, the inputs of the S-Function block are the fuel flow and shaft power. Here, the shaft power represents either the electrical power extracted from a generator or the torque applied to the shaft by the starter. When used as starter power, the signal is negative. The outputs of the S-Function block are the turbine inlet temperature and the shaft speed. Additionally, the state and derivative parameters to be used in the model can also be specified here. This ensures that these parameters are automatically updated at each simulation step. The starting point of the transient analysis is determined by the initial value of the state parameter.

After connecting the NPSS model to Simulink via the S-function, a sensor block is added to model the NPSS outputs more realistically. The purpose of this sensor block is to simulate actual sensor delays. For instance, temperature sensors have high time constants, which causes sudden temperature changes to reach the controller (ECU) with a delay. The sensor's time constant depends on its physical construction, the

measured quantity, the environmental conditions, and the characteristics of the electronic circuitry. Therefore, the time constant of each sensor differs. The time constant values used in this study are selected based on the literature [26].

The schematic of the turbojet engine transient model implemented in Simulink is shown in **Figure 3.5**.

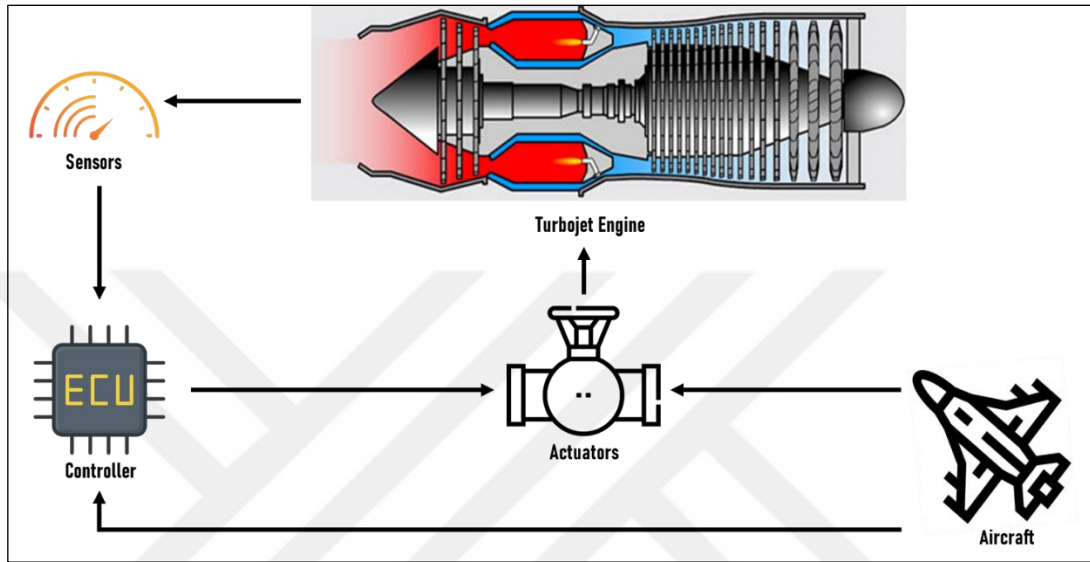


Figure 3.5: Turbojet engine transient model shema

A controller block is implemented to process the data from the sensors and the inputs from the aircraft controller, which include parameters such as PLA (Power Lever Angle), atmospheric pressure, Mach number, and altitude. This controller regulates the fuel flow according to the received inputs and operating conditions. Additionally, it controls the generator and the starter depending on the current operating mode.

As with the sensor block, the actuator block models the delays of the fuel metering pump, starter, and generator. The time constant values of these components are also taken from the literature [26].

Multiple control logics are implemented within the controller. For example, the controller used during starting is different from the one used during normal operation. A more comprehensive description of the controller is provided later in this chapter.

Within Simulink, the total simulation time and step time can be defined. All starting analyses are conducted under SLS ISA conditions, where engine start durations typically remain below 60 seconds. Therefore, the simulation time is set to 60 seconds.

In transient analyses, the step time is chosen to balance simulation accuracy and computational cost. A large step time may fail to capture fast-varying parameters, such as spool speeds, torques, and temperatures, while an excessively small step time increases simulation duration and computational effort.

In this study, a step time of 0.01 s is selected, considering dynamic events such as engine starting and acceleration. This value ensures sufficient accuracy in capturing rapid transient variations while maintaining a reasonable simulation time.

3.3.1. Above-Idle

The term above-idle refers to the operating region between idle and maximum power. Transient operations in this region require careful control, as there is still a risk of compressor surge or exceeding structural limits. Therefore, acceleration and deceleration must be properly managed.

Each PLA setting corresponds to a corrected shaft speed. When the pilot adjusts the throttle, the engine attempts to change from its current speed to the speed corresponding to the requested PLA. This transition must occur within defined limits. To facilitate this, a PI controller is implemented in Simulink. The controller's objective is to achieve the pilot-requested speed safely and as quickly as possible.

In this study, the above-idle region is used solely for comparing the GasTurb and Simulink models. All other analyses focused on the sub-idle region; consequently, the above-idle controller is not extensively refined.

GasTurb supports transient analysis. Parameters such as PLA, power off-take (POT) representing the shaft power consumed by engine-driven accessories, altitude, and ambient temperature can be varied over time to simulate transient behavior. In real operation, altitude and ambient temperature change slowly, whereas PLA and POT can vary rapidly, as they are typically under pilot control. Therefore, when comparing Simulink and GasTurb models, PLA and POT are provided as time-dependent schedules. These schedules are shown in **Figure 3.6**.

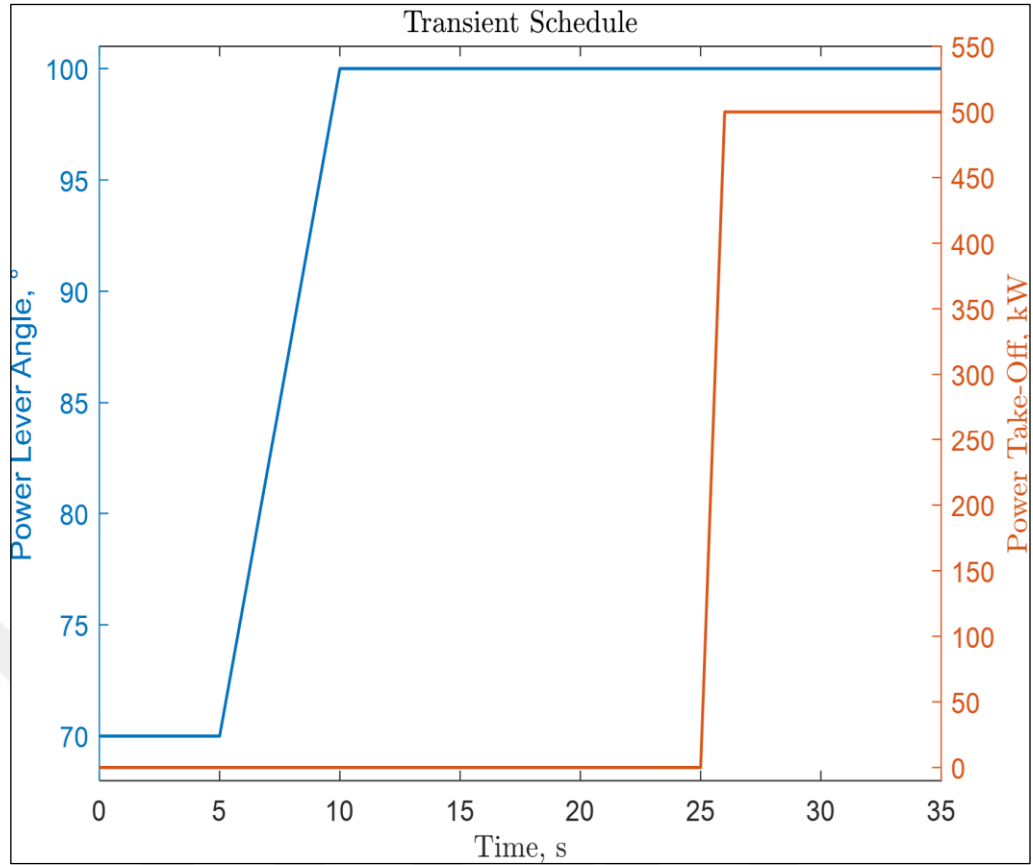


Figure 3.6: Transient analysis schedule

The comparison of the transient analysis results obtained from the transient model developed in Simulink and the GasTurb model is presented in 0.

3.3.2. Sub-Idle

In the GasTurb model, the turbine and compressor maps embedded within the software only contained above-idle data, that is, data corresponding to speeds above approximately 50% for the compressor and 80% for the turbine. Since the focus of this study is the starting process, sub-idle maps extending down to zero speed are required. Similarly, the other component characteristics, such as burner efficiency and the pressure losses in the burner, inlet, and exhaust, are also defined only for above-idle conditions. To achieve a smooth and stable starting analysis, these component characteristics also needed to be extrapolated down to zero speed or zero mass flow.

3.3.2.1. Sub-Idle Turbomachinery Maps

The greatest majority of performance analysis conducted on gas turbine engines focus on above-idle regimes, where the engine operates most of its time. In these regions,

high accuracy performance maps can be obtained through component testing and CFD analysis. However, studies examining sub-idle operating conditions often lack direct access to test data. Also, performing CFD analyses at low rotational speeds present significant challenges due to the physically complex nature of the flow in this regime. The presence of unsteady and separated flow behavior, transitional flow phenomena, low Reynolds numbers and pronounced heat transfer effect makes accurate simulation highly demanding. Therefore, in the early phases of the engine design and analysis, estimated performance maps for sub-idle regions are required. Various methods have been developed in the literature to obtain sub-idle maps such as extrapolation and interpolation. In this study, physical based interpolation method will be examined.

As illustrated in **Figure 3.7**, above-idle compressor maps typically present corrected mass flow, pressure ratio, efficiency, and beta lines within a single dataset. However, as the pressure ratio approaches unity, efficiency values exhibit a discontinuity, making interpolation impossible. Kurzke suggests that, for sub-idle conditions, specific torque can be used instead of efficiency [5]. In this study, specific torque (torque/corrected mass flow) is used in place of efficiency. The final map therefore includes corrected mass flow, pressure ratio, specific torque and beta lines.

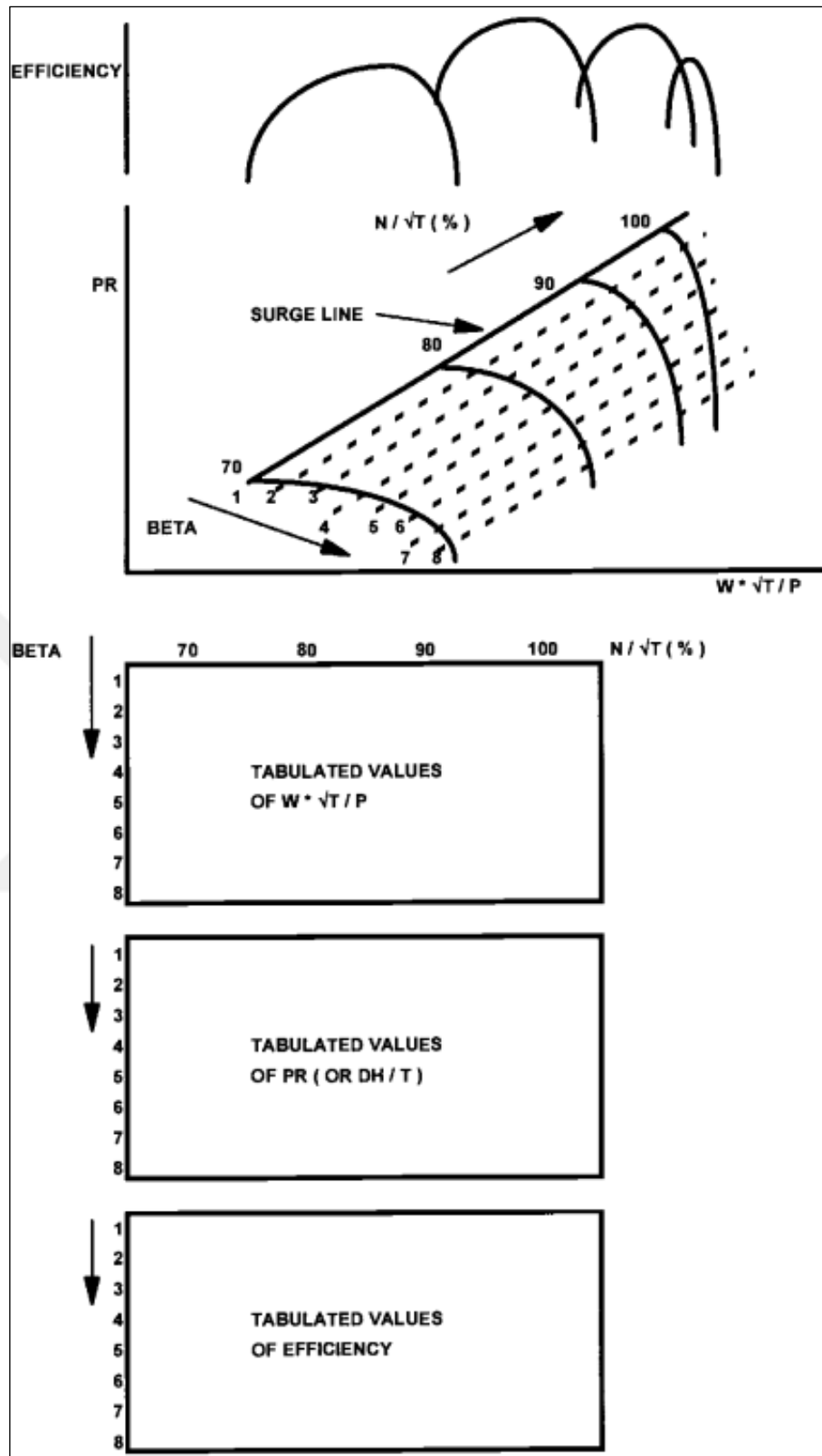


Figure 3.7: Typical compressor map dataset [1].

Unlike the compressor dataset, the turbine dataset does not include beta lines. Instead of beta lines, the turbine dataset uses PR. A typical turbine dataset is shown in **Figure**

3.8. A turbine map contains performance characteristics such as component efficiency, pressure ratio, and corrected mass flow rate.

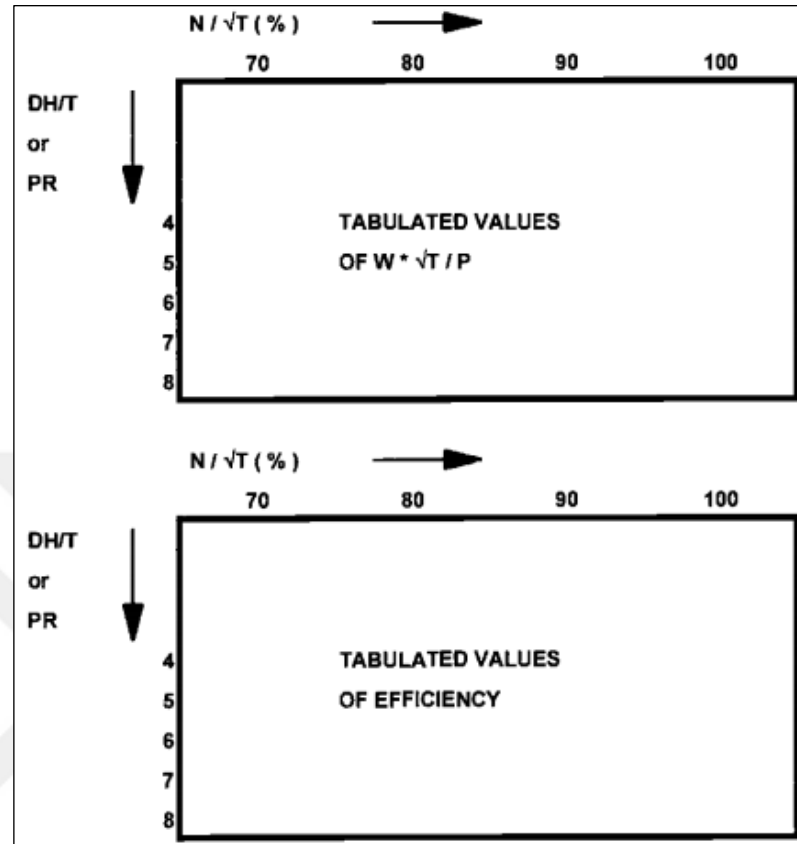


Figure 3.8: Typical turbine map dataset

A code to generate compressor and turbine sub-idle map is written in MATLAB as an in-house tool. Default turbojet engine turbomachinery maps in GasTurb are interpolated to generate the sub-idle maps using this code.

This method begins by estimating the 0-speed line through detailed analysis of the flow under lock rotor conditions. Once 0-speed curve is established, the remainder of the turbomachinery map can be constructed via interpolation, resulting in a more accurate representation of the low speed performance characteristics.

3.3.2.1.1. Compressor Sub-Idle Map

First, the standard compressor map used in the GasTurb turbojet engine model, as shown in **Figure 3.9**, was implemented in Smooth-C [23], where the available above-idle data, such as torque characteristics and β -parabolas, were used as the basis for extending the compressor map into the sub-idle regime.

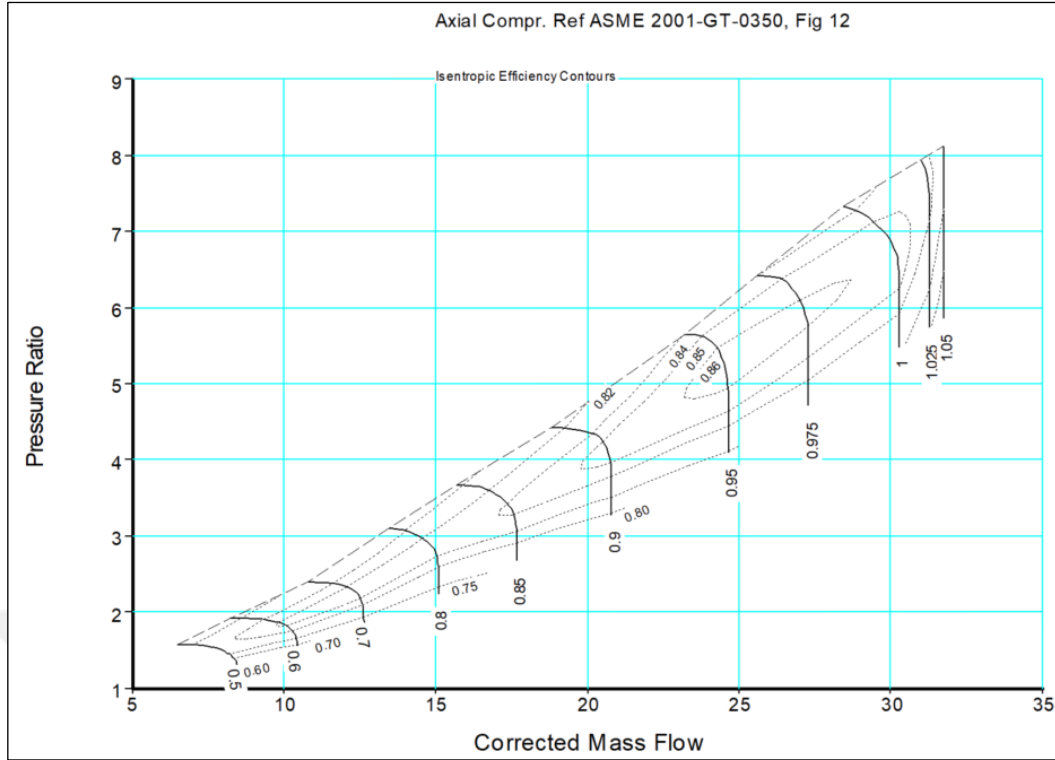


Figure 3.9: GasTurb standard turbojet engine compressor map [6].

The sub-idle compressor map is presented in two parts: the pressure ratio map and the torque map.

(a) The 0-Speed Line of Pressure Ratio Map

In the locked rotor condition, while shaft speed is zero, the compressor effectively behaves like a duct with internal restrictions, as no shaft work is imparted to the flow due to the stationary rotor. As a result, total temperature remains constant throughout the passage, as the total pressure gradually decreases between the inlet and outlet as a result of viscous losses and diffuser-related effects. Under the assumption of incompressible flow, this behavior leads a parabolic relationship between pressure ratio and mass flow rate along the 0-speed line [23]. The equation of the parabola is given in Equation 1.

$$PR = 1 - k_{PR} * W_c^2 \quad (3.21)$$

The compressor k_{PR} parameter is employed to generate the 0-speed line, and results indicated that it can significantly influence the interpolation of $PR - W_c$ characteristics in the compressible part of sub-idle regime. However, it should be noted that most of

the engine starting process takes place within the incompressible flow regime, where the influence of the k_{PR} parameter is negligible, particularly for single-spool turbojet engines. [9].

Before generating the sub-idle map, identical beta lines are used for both the sub-idle and above-idle maps to ensure visual consistency in the plots. To achieve this, the above-idle map is imported into the Smooth-C [23] program and the parabolic coefficients corresponding to the Beta 0 and Beta 1 lines are recorded. These coefficients are then used in MATLAB to generate the beta lines. In this example, 20 beta lines are created by interpolating between Beta 0 and Beta 1. Subsequently, the intersection points between the generated 0-speed line and these beta lines are extracted.

Figure 3.10 presents the above-idle map imported into Smooth-C, along with the parabolic coefficients corresponding to Beta 0 and Beta 1. The Beta 1 line is initiated at the point where the mass flow is zero and the pressure ratio is 1. The Beta 0 line, on the other hand, is initiated at the point where the mass flow is zero and the pressure ratio is 0.8, considering potential future windmilling studies. Subsequently, additional beta lines are inserted in MATLAB to obtain a total of 20 beta lines. These beta lines are generated using linear interpolation.

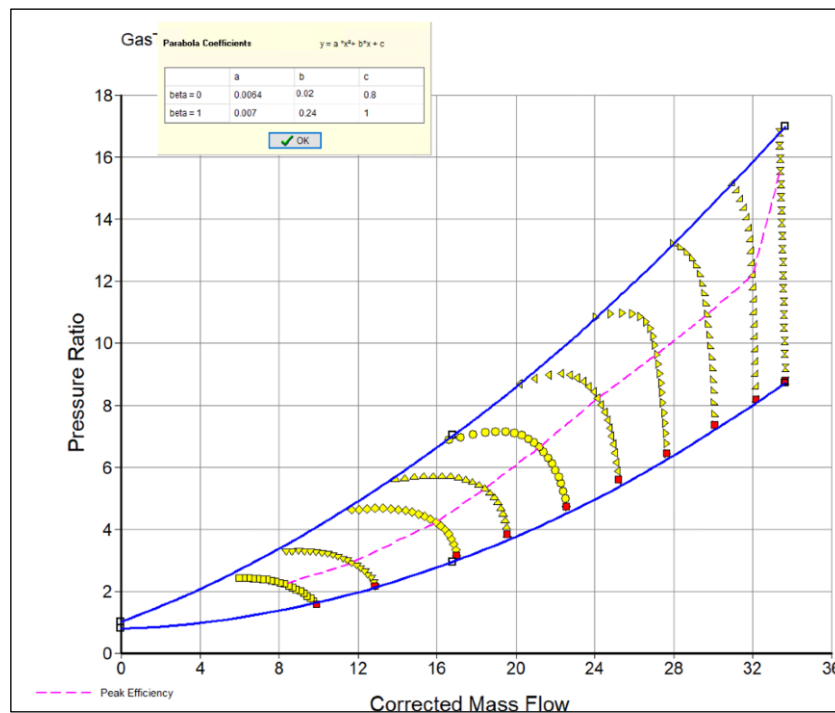


Figure 3.10: Above-idle compressor map imported into Smooth-C

Turbojet compressor 0-speed lines for different k_{PR} parameters are generated and shown in **Figure 3.11**.

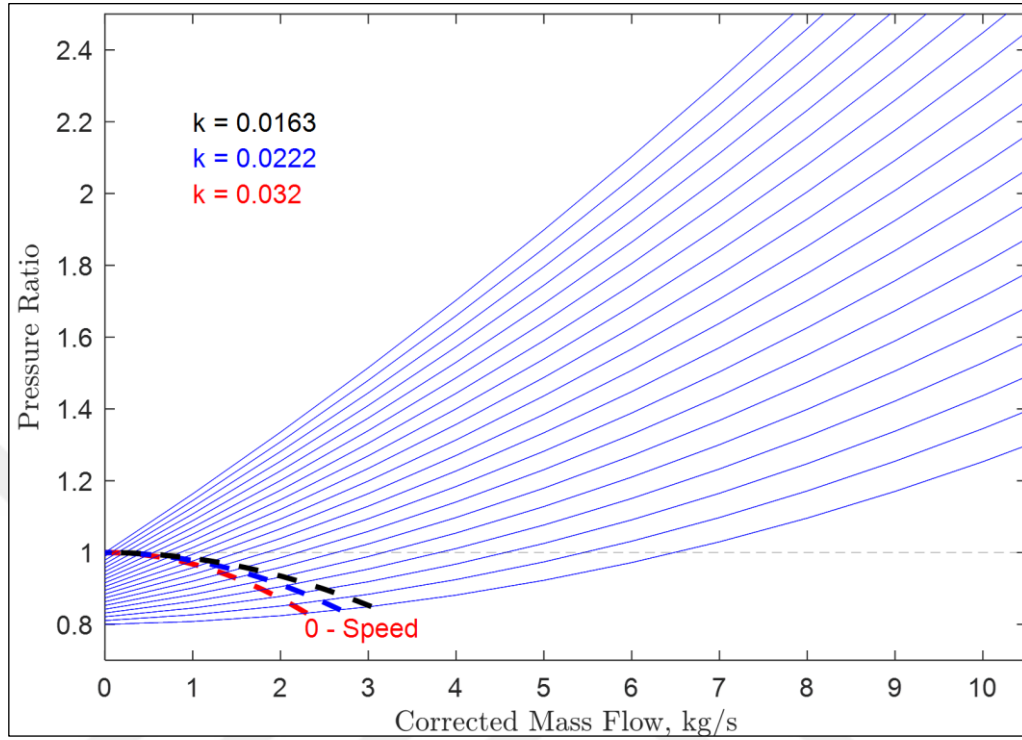


Figure 3.11: Compressor map 0-speed line for different k_{PR} parameters

(b) Interpolation of Pressure Ratio Map

The last speed line (i.e., the lowest one) of the above-idle map loaded into the Smooth-C program is exported to MATLAB. In this example, the corresponding speed is 0.5. Intermediate speed lines between the estimated 0-speed line and the 0.5 speed line are interpolated using the previously generated beta lines. As stated in SmoothC9 Manual [23], the lower portion of the speed–flow relationship along a β -line exhibits an almost parabolic behavior. So it is important to note that, during this interpolation process, the mass flow rate varies proportionally with the square of the rotational speed.

In the previous section, 0-speed lines are generated for different k_{PR} parameters, and it is discussed that the effect of k_{PR} on engine starting performance is minor. From this point onward, a constant k_{PR} value of 0.0222 is used. **Figure 3.12** presents the interpolated sub-idle pressure ratio map.

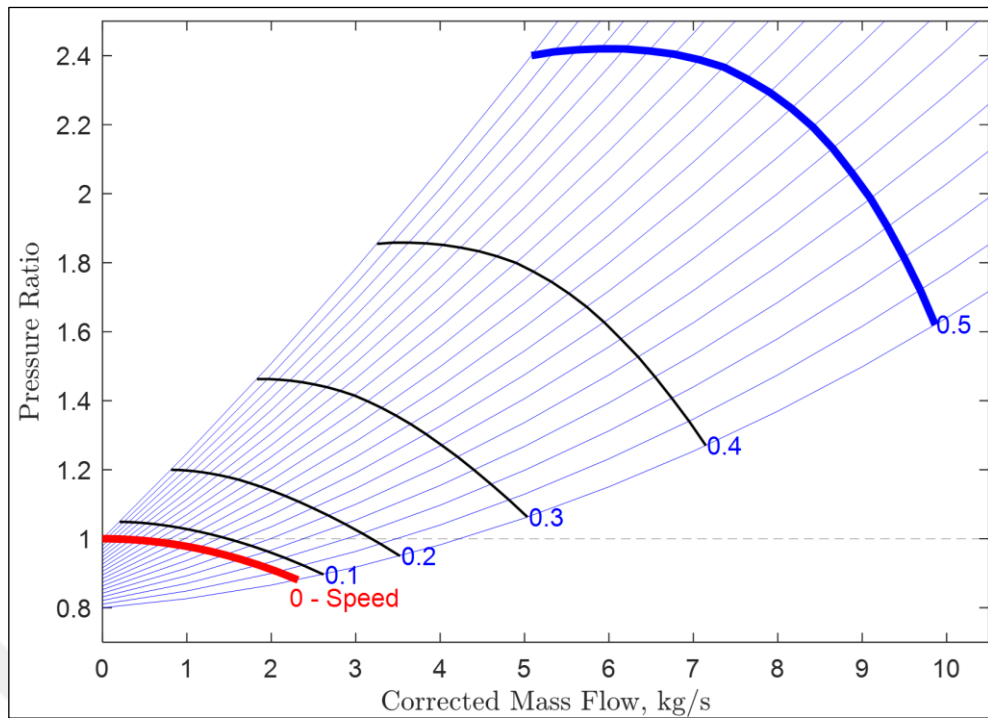


Figure 3.12: Sub-idle compressor pressure ratio map with interpolated speed lines

(c) Surge Line

Due to the absence of surge data below 50% speed, the surge line in the low-flow region is approximated by a straight line connecting the known surge point at 50% speed to the physical limit at zero mass flow and a pressure ratio of 1. This linear approach is based on the assumption of limited slope variation in this part of the compressor map and provides a simple estimate of the low-speed surge behavior in the absence of additional experimental data. **Figure 3.13** shows the sub-idle compressor map surge line.

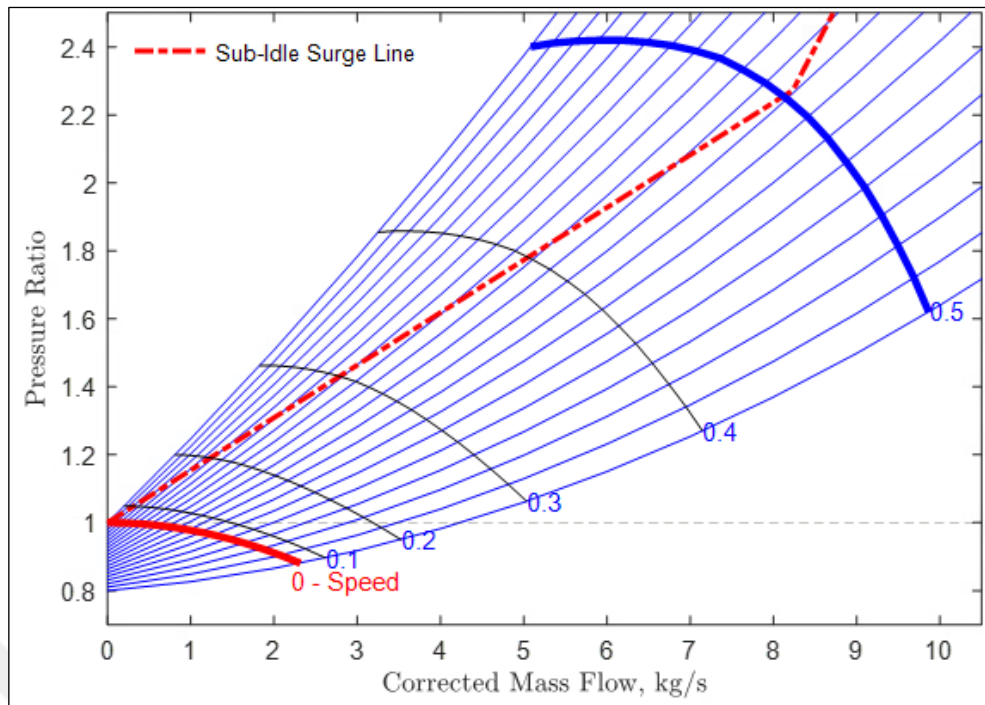


Figure 3.13: Sub-idle compressor map surge line

(d) Torque Map

Kurzke [5, 15] states that torque values at given speed tend to become more linear as mass flow decreases, and that the resulting torque curves are approximately parallel across all speed lines. This approach is based on incompressible flow theory under low Mach number and small density variation assumptions. Under these conditions, torque primarily varies with mass flow and also increases approximately proportionally with speed, making the representation with parallel curves in the corrected coordinates a reasonable approximation. **Figure 3.14** presents the straight torque/flow lines for a single stage transonic fan [5].

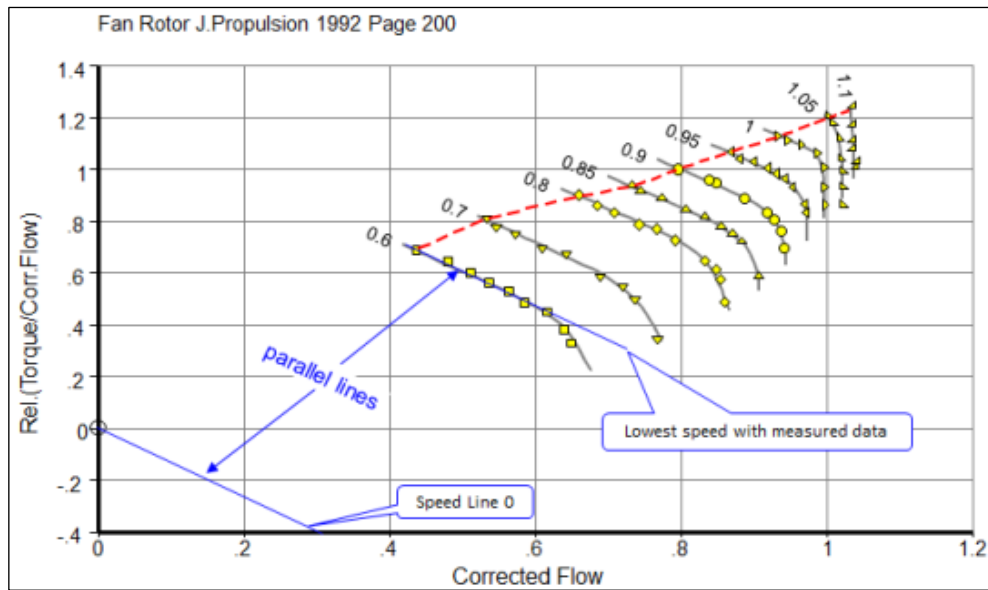


Figure 3.14: Straight torque/flow lines

The specific torque curve corresponding to the lowest speed line in the map imported into Smooth-C is transferred to MATLAB. By calculating the slope of this curve, the 0-speed line is obtained. During the obtaining of this line, the range of corrected mass flow values from the pressure ratio map are used. **Figure 3.15** presents the 0-Speed relative corrected torque (Torque/Corrected Mass Flow) curve of Turbojet compressor.

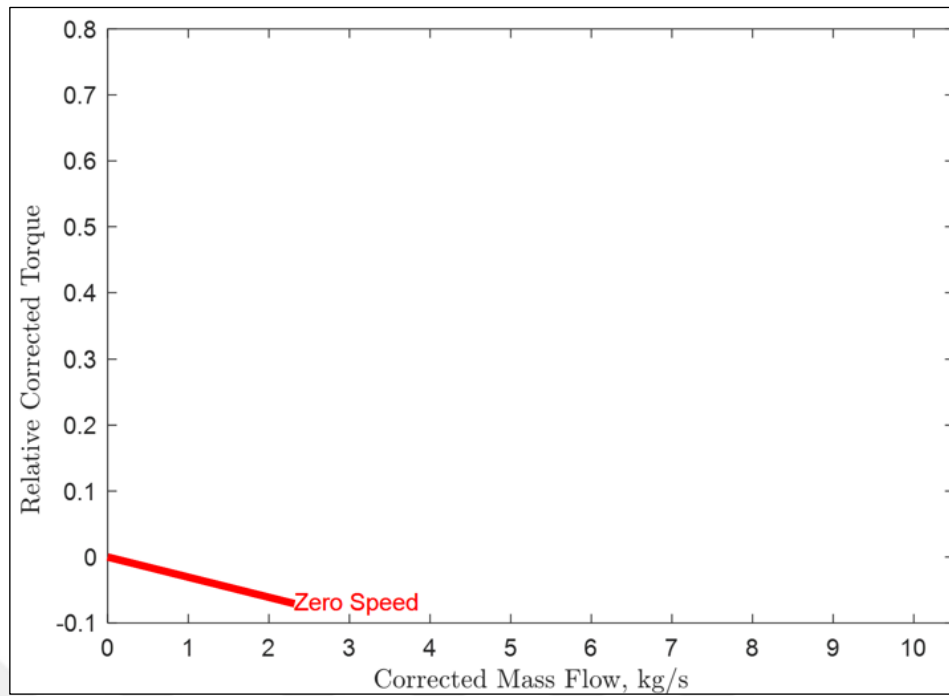


Figure 3.15: Compressor 0-speed relative torque line

Similar to the approach used in the pressure ratio map, intermediate speed lines between the last and 0-speed line are generated through linear interpolation. **Figure 3.16** presents the interpolated sub-idle torque map.

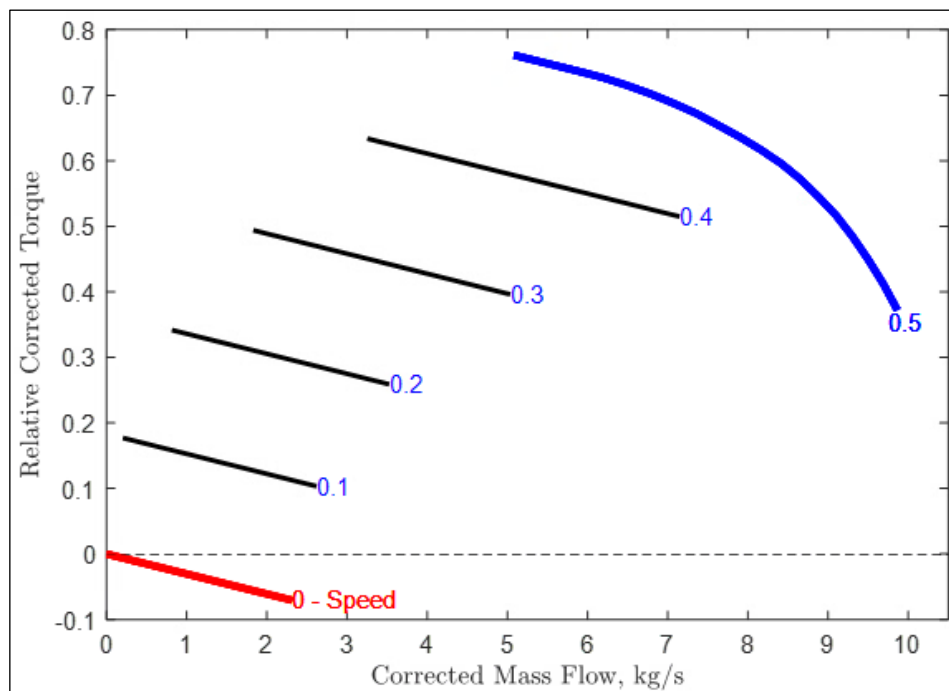


Figure 3.16: Sub-idle compressor torque map with interpolated speed lines

3.3.2.1.2. Turbine Sub-Idle Map

First, the standard turbine map used in GasTurb turbojet engine model, as shown in **Figure 3.17**, was implemented in Smooth-T [24].

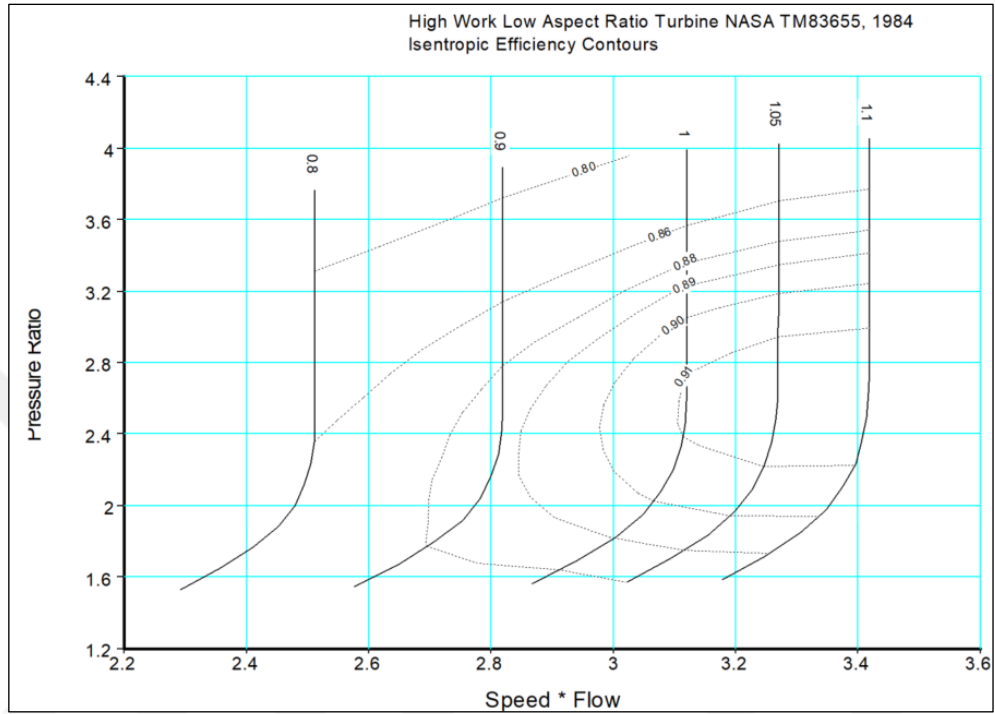


Figure 3.17: GasTurb standard turbojet engine turbine map

Similar procedures to those applied to the compressor are also carried out for the turbine sub-idle map. Kurzke [14, 15] provides a detailed theoretical explanation of how the low-speed regions of the turbine map can be derived. The sub-idle pressure ratio and torque maps generated by in-house tool are presented in **Figure 3.18** and **Figure 3.19**.

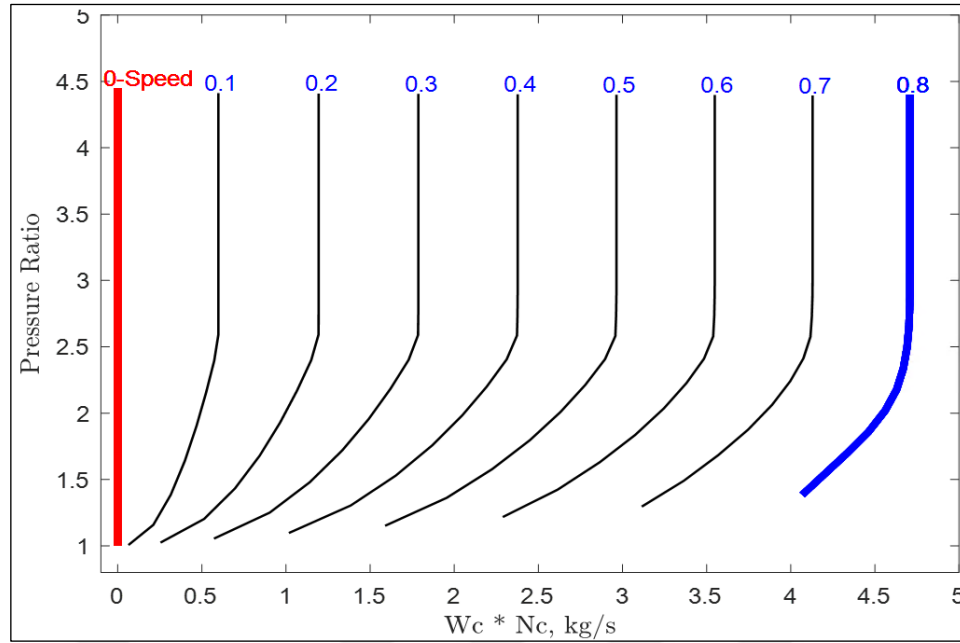


Figure 3.18: Sub-idle turbine pressure ratio map

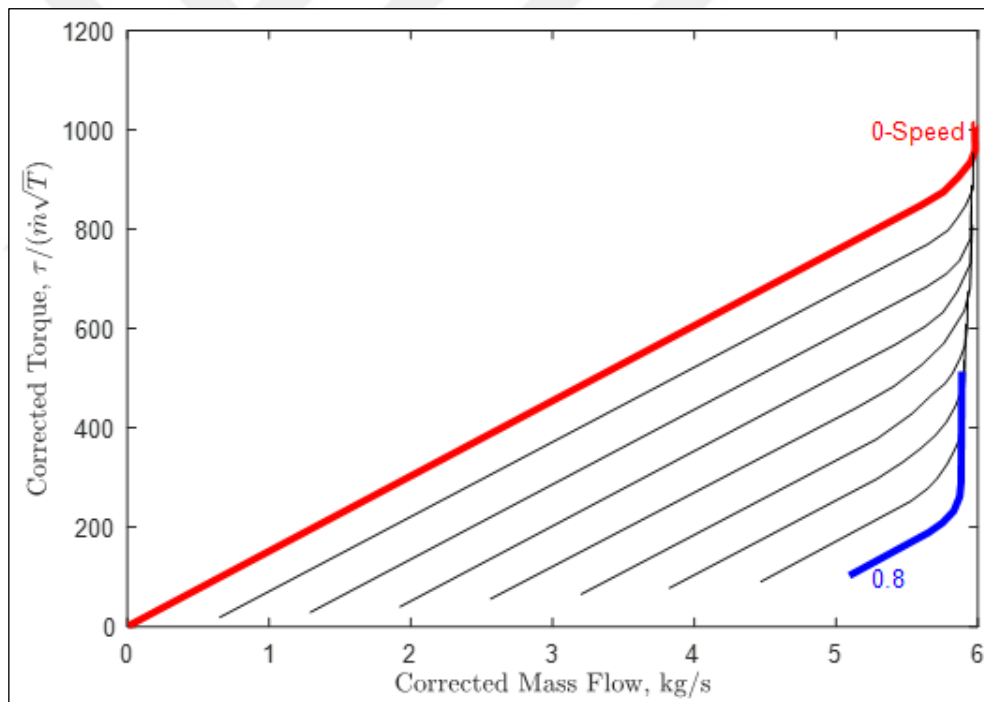


Figure 3.19: Sub-idle turbine torque map

3.3.2.2. NPSS Elements

The sub-idle compressor and turbine maps derived in previous sections are not directly compatible with implementation in NPSS. In its standard configuration, the CompressorRlineMap element in NPSS operates based on pressure ratio, corrected mass flow, efficiency and Rline parameters. However, with the transition to torque

based maps, the efficiency parameter is omitted and replaced by torque. Consequently, it became necessary to modify both the CompressorRlineMap and Compressor elements to handle this change. A schematic representation of the torque-based compressor subroutine is shown in **Figure 3.20**.

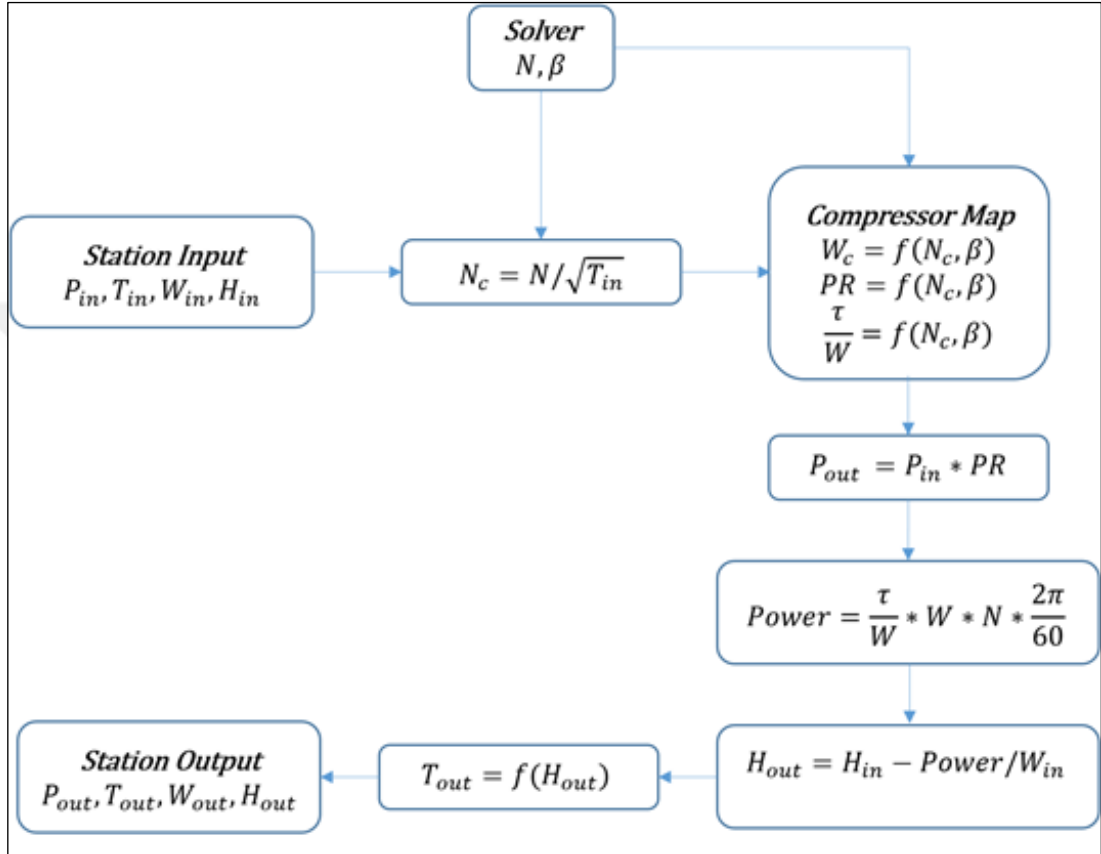


Figure 3.20: Schematic representation of torque-based compressor sub-routine

Similarly, for turbine modeling, the conventional approach in NPSS involves the use of pressure ratio, corrected mass flow and efficiency parameters. With the transition torque based turbine maps, efficiency is replaced with torque similar to compressor, requiring corresponding updates to the TurbinePRmap and Turbine elements.

3.3.2.3. Sub-Idle Component Modelling

Extending the compressor and turbine maps down to zero speed is not sufficient to accurately resolve starting analyses. The pressure loss and efficiency characteristics of other engine components must also be adapted for sub-idle conditions. If these characteristics are not modified accordingly, extrapolating above-idle component

characteristics to zero mass flow may result in unrealistic pressure drops or rises within the components in the absence of flow. This, in turn, can lead to convergence issues during simulation.

3.3.2.3.1. Inlet, Duct and Burner Pressure Losses

Inlet, duct, and burner pressure losses are assumed to be directly proportional to the square of the inlet corrected mass flow [21]. Since the pressure losses at the design point are known and the pressure loss becomes zero at zero mass flow, the pressure losses in these components could be extrapolated for sub-idle conditions.

The design point inlet, duct, and burner pressure losses are 1%, 2% and 3% respectively. The off-design inlet, duct, and burner pressure losses are generated by using Equation 3.22 and presented in **Figure 3.21**, **Figure 3.22**, and **Figure 3.23**, respectively.

$$\frac{1 - \frac{P_2}{P_1}}{\left(1 - \frac{P_2}{P_1}\right)_{dp}} = \left(\frac{\frac{W_1 \cdot \sqrt{R \cdot T_1}}{P_1}}{\left(\frac{W_1 \cdot \sqrt{R \cdot T_1}}{P_1}\right)_{dp}} \right)^2 \quad (3.22)$$

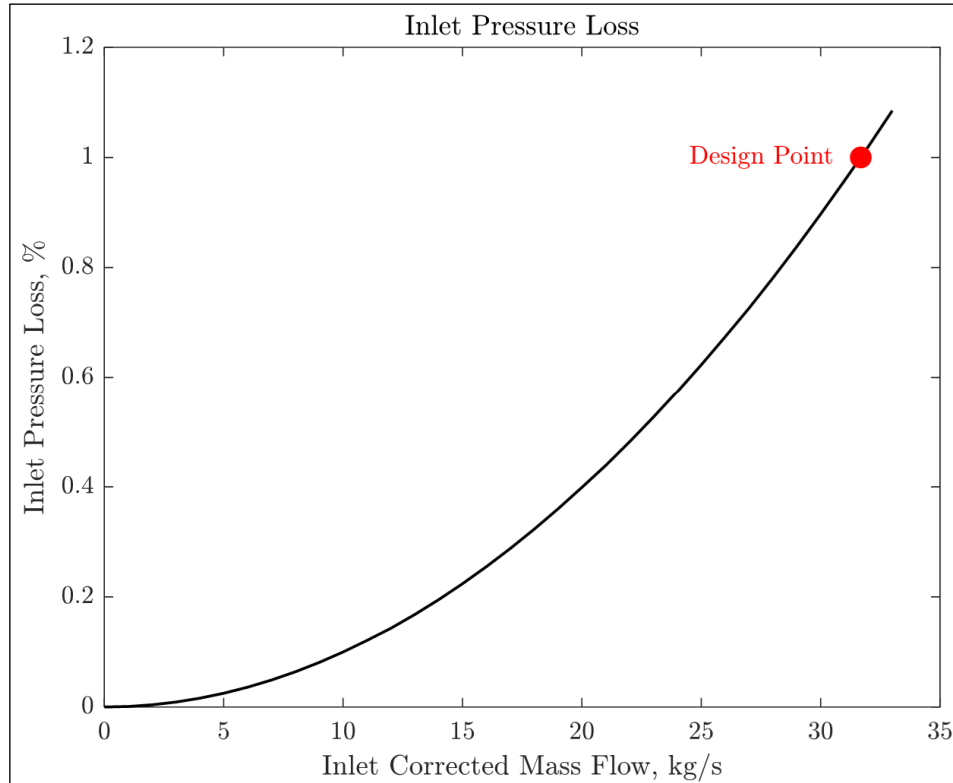


Figure 3.21: Inlet pressure loss

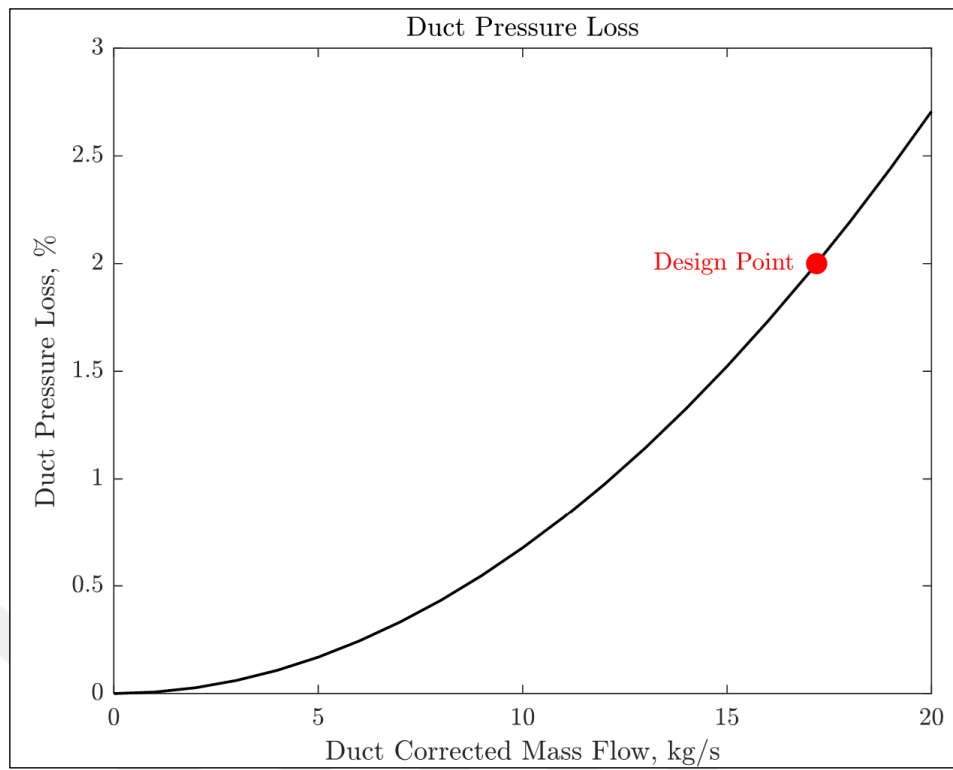


Figure 3.22: Duct pressure loss

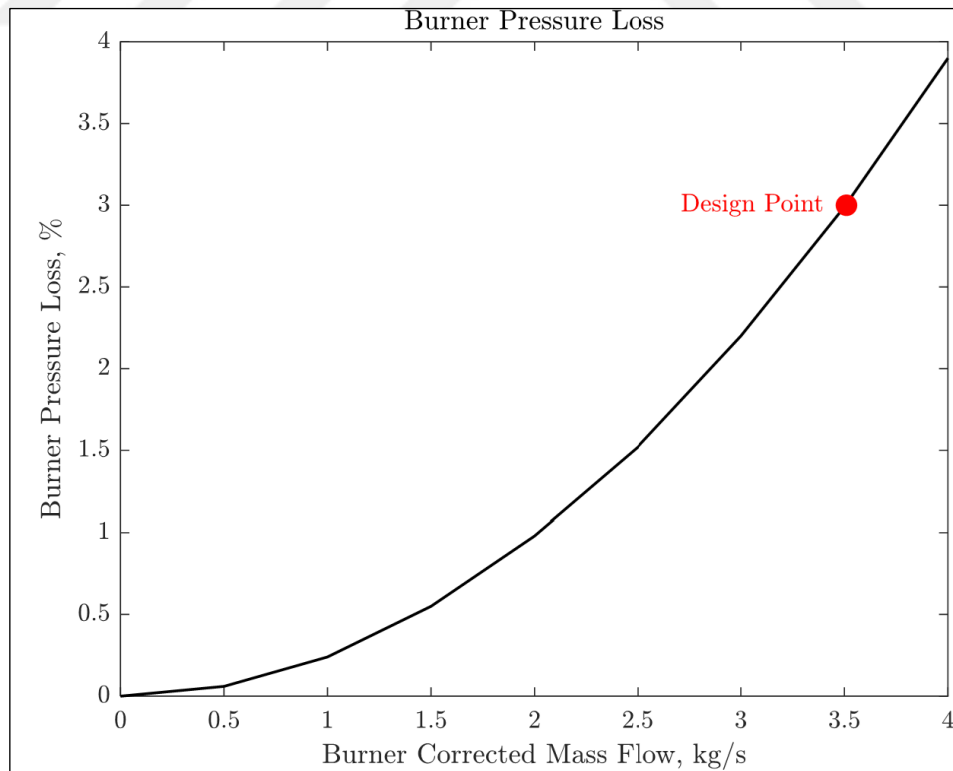


Figure 3.23: Burner pressure loss

3.3.2.3.2. Burner Efficiency

The combustion efficiency under steady-state conditions can be correlated with burner loading as in Equation 3.23 [21]. Burner loading formula is given in Equation 3. The constant a in this formula is related to the design-point efficiency and its formula is given in Equation 3.25. The burner part load constant b is taken 1.6 as default in GasTurb.

$$\eta = 1 - 10^{a+b \cdot \log(\Omega/\Omega_{dp})} \quad (3.23)$$

$$\Omega = \frac{W_{31}}{P_3^{1.8} \cdot e^{T_3/300K} \cdot Vol} \quad (3.24)$$

$$a = \log(1 - \eta_{dp}) \quad (3.25)$$

The burner efficiency at the design point is 0.9999. The steady-state burner efficiency correlation as a function of Ω is given in **Figure 3.24**.

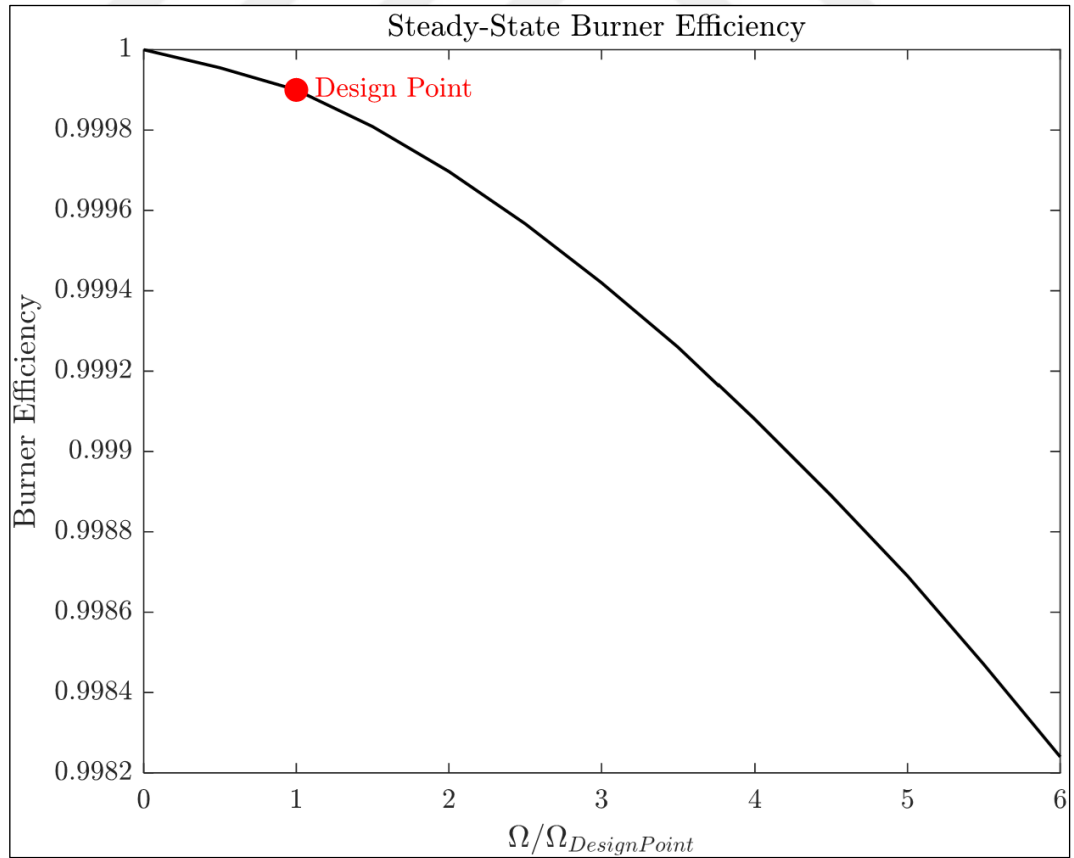


Figure 3.24: Steady-state burner efficiency

However, as noted by Walsh & Fletcher [2], burner efficiency can drop to as low as 10–50% during light-off. Instead of removing the steady-state efficiency correlation, an additional correction factor is applied for sub-idle burner efficiency.

In this study, burner efficiency during light-off is not a primary focus. Therefore, this factor is conservatively set to 0.6 during light-off and adjusted to 1.0 for idle and higher operating speeds, as presented in **Figure 3.25**. The final burner efficiency is calculated using Equation 3.26.

$$\eta_{burner} = \eta * c_{burn_eff} \quad (3.26)$$

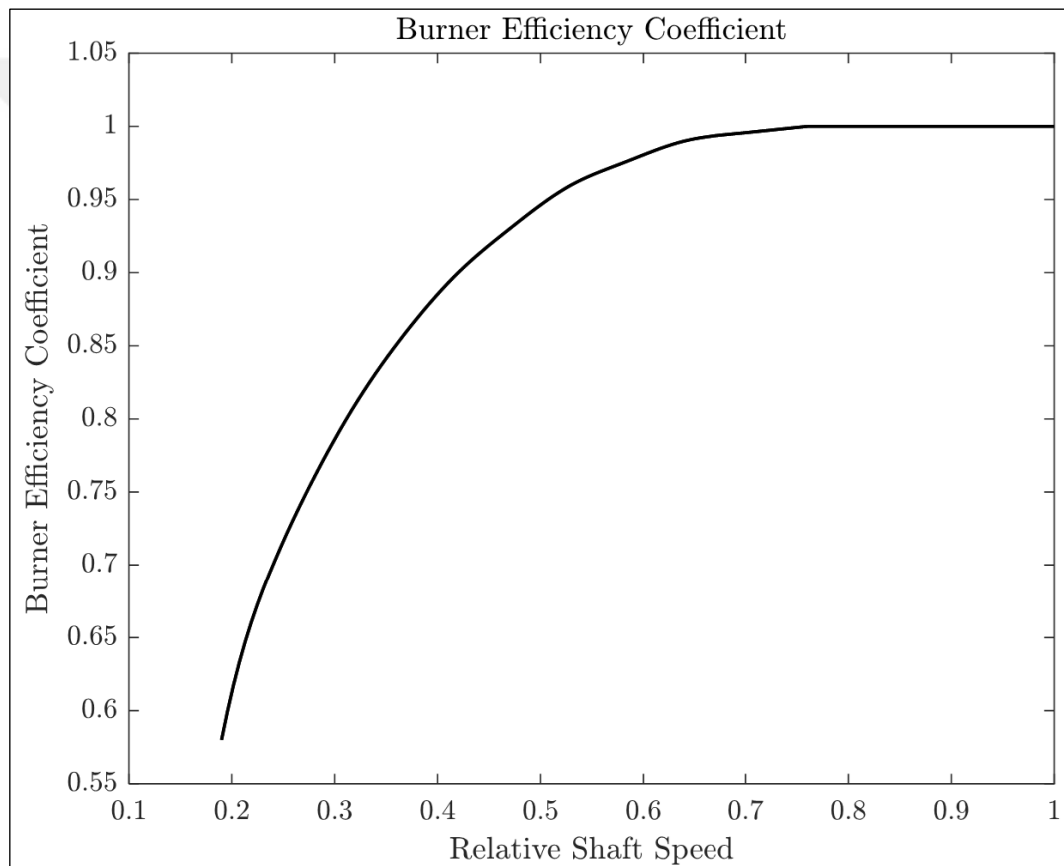


Figure 3.25: Burner efficiency coefficient

3.3.2.4. Starting

Starting is a highly complex process in which every selection is critical. Some of these selections include the light-off speed, starter power, starter cut-out speed, and fuel schedules. These parameters are discussed individually below. A typical starting sequence of a turbojet engine is shown in **Figure 3.26**.

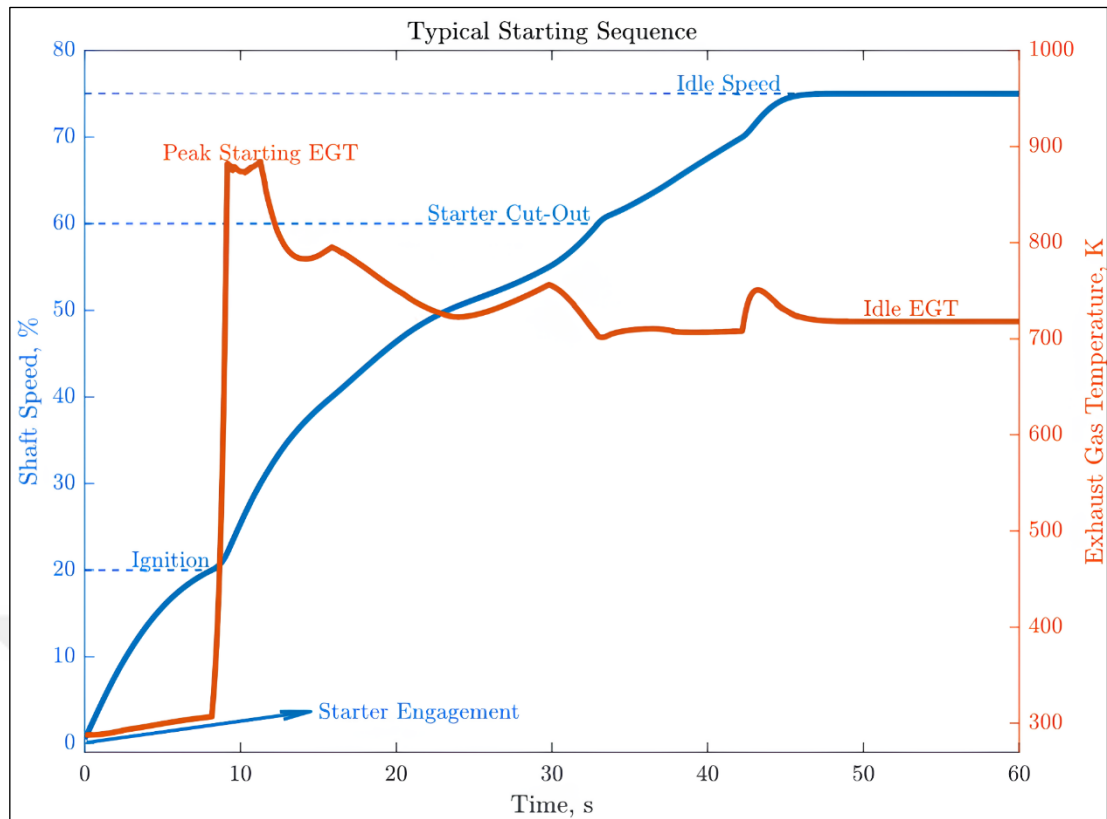


Figure 3.26: Typical starting sequence

3.3.2.4.1. Light Off – Ignition

Figure 3.27 shows a starting operating line on the compressor map. As seen in this figure, if the light-off point is selected slightly further downstream, it can enter the hang start region. Therefore, the light-off point is highly critical.

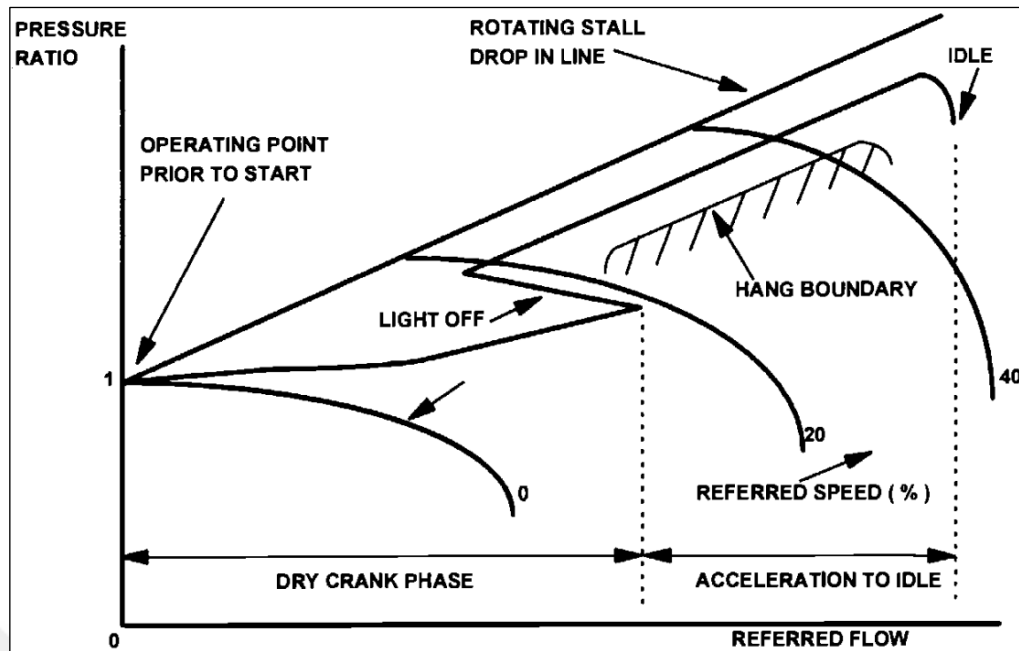


Figure 3.27: Starting operating line [1].

According to Walsh & Fletcher [2], ignition occurs between 15% and 25% of the high-pressure spool speed. In this study, the ignition speed is taken as 20% of the shaft rotational speed.

3.3.2.4.2. Starter Selection

The starter power is a critical selection due to the aircraft's weight requirements. If an unnecessarily large starter is chosen, it adds extra weight to the aircraft. Conversely, if it is undersized, there is a risk of a hung start, or the starting time may be too long to meet operational requirements. Determining the starter power before reaching the testing phase can significantly shorten the project schedule.

Before ignition, the power produced by the turbine is very low because the pressure and temperature of the air entering the turbine are low. In this pre-ignition phase, the majority of the power required by the compressor is supplied by the starter. However, once ignition occurs, the air temperature at the turbine inlet rises rapidly, and the turbine begins to perform work significantly. From this point onward, the turbine carries the load of the compressor and other accessories, while the starter remains engaged with the shaft only until the self-sustain speed, ensuring that the engine continues to accelerate on its own. Once the engine reaches a speed at which it can accelerate independently, the starter cuts out.

The power required by the compressor increases with shaft speed. The most critical speed for determining starter power is the ignition speed because this is where the starter alone bears the maximum load. In the early design phase, before sub-idle operations have begun, the power at a point above idle can be estimated by extrapolation using the cube law method [2]. In this study, the initial starter power is determined using the cube law method and subsequently validated with the developed starting model. To find the compressor power demand at any given speed using the cube law, it is sufficient to know the compressor power at a known speed. This method can be expressed by Equation 3.27:

$$P = P_{ref} \left(\frac{N}{N_{ref}} \right)^3 \quad (3.27)$$

Since the shaft speed and compressor power at the turbojet engine's design point are known, this point is used as a reference. The design-point speed is 100%, and the compressor power is 11,500 kW. Substituting these values into Formula 7 yields a compressor power requirement of 92 kW at 20% ignition speed. In fact, the turbine produces power at this point; however, its output cannot be directly determined using Equation 7. This is because the turbine normally operates at high temperature and high pressure to achieve full performance. Prior to ignition, however, there is no combustion, and the temperature of the air entering the turbine is considerably low. Therefore, when estimating the initial starter power, the turbine's power is neglected.

3.3.2.4.3. Handling Bleed

Walsh & Fletcher [2] states that the use of handling bleed can lower the compressor operating line without modifying the compressor map, thereby moving it away from the surge line. The effect of handling bleed on compressor map is presented in **Figure 3.28**.

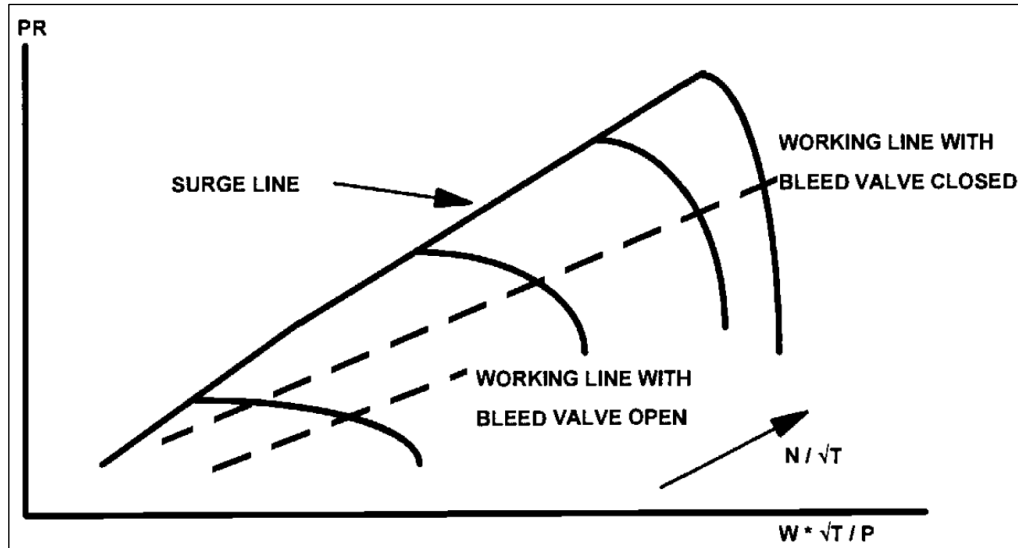


Figure 3.28: Effect of handling bleed on compressor map [1].

In many gas turbine engines, bleed air is extracted from the compressor outlet during engine start to prevent compressor surge. This surge bleed is typically controlled using a fixed valve opening due to its simplicity. However, as demonstrated by Sexton [12], employing a variable surge valve schedule during the starting phase can reduce turbine inlet temperatures, thereby decreasing thermal gradients and contributing to an extended turbine life.

In this study, the effects of applying surge bleed during engine start, either at a fixed rate or using a variable schedule, are investigated. Since the regions approaching surge appear between 20% and 65% shaft speed, the variable handling bleed schedule is implemented only within this speed range. As shown in **Figure 3.29**, analyses are performed using two different surge bleed schedules. The results will present in 4.5.

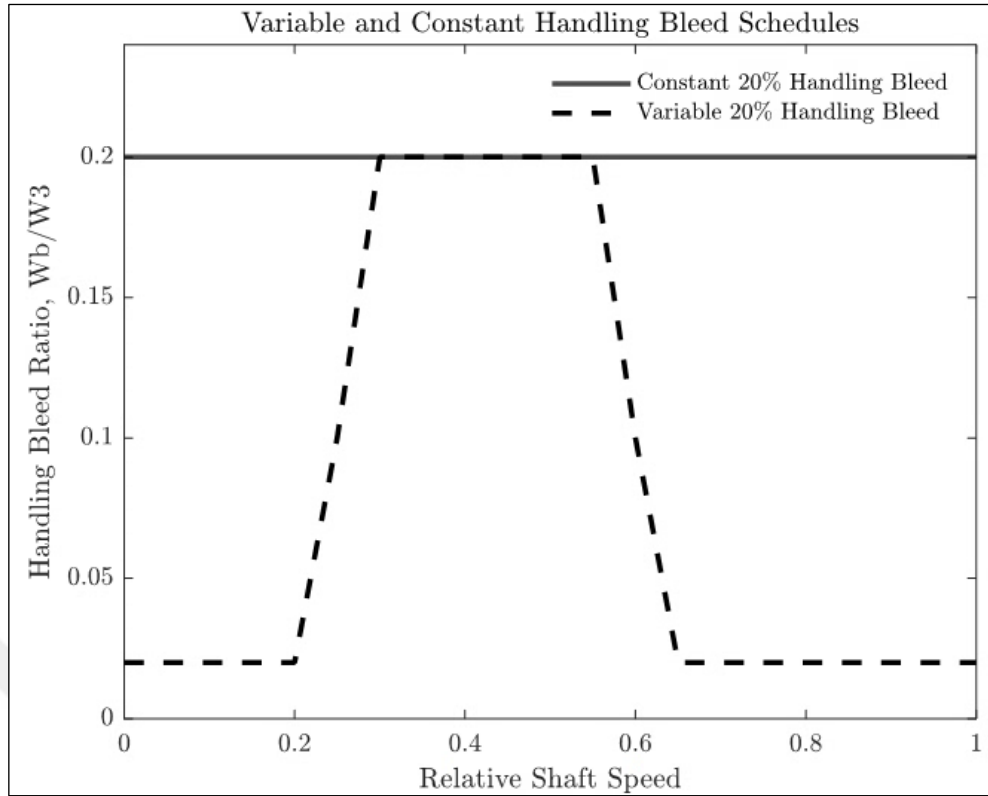


Figure 3.29: Variable and constant handling bleed schedules during starting

3.3.2.4.4. Starting Control

During engine start, there are three fuel phases [2]: light-off flat, starting acceleration schedule, and idle controller. These fuel schedules should be kept as low as possible to avoid surge and exceedance of temperature limits; on the other hand, they should be high enough to prevent hang starts and to meet the starting time requirements.

The fuel delivered during ignition can be either a flat schedule, as shown in **Figure 3.30**, or a variable schedule depending on the engine RPM. In some engines, ignition is detected using the EGT sensor, during which the light-off fuel schedule is disabled. In other engines, to ensure that the delivered fuel is sufficient, the schedule may continue up to a certain shaft speed. In this study, as illustrated in **Figure 3.31**, a fuel schedule varying with shaft speed is defined between 20% and 30% of the shaft speed.

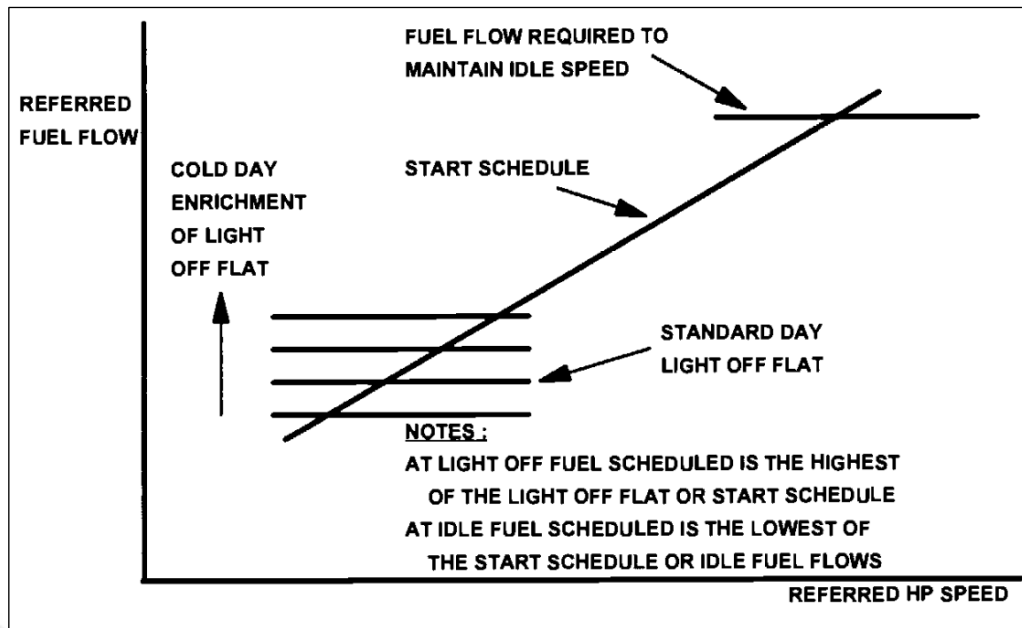


Figure 3.30: Flat fuel schedule [1].

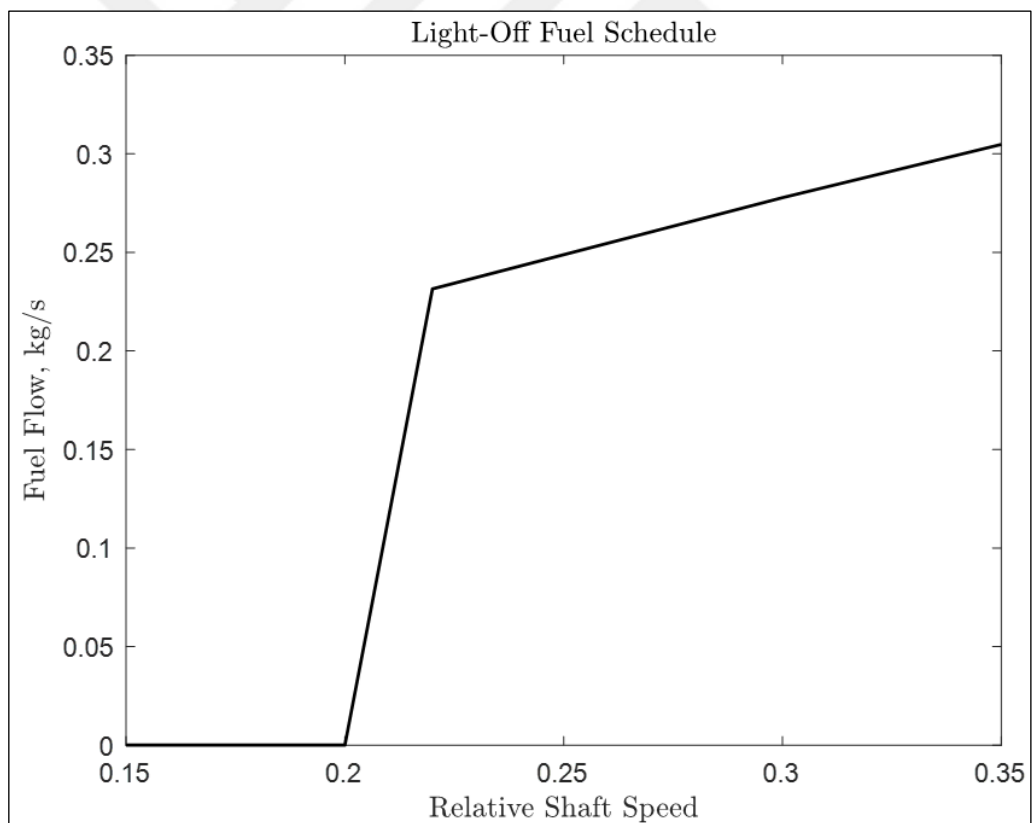


Figure 3.31: Light-off fuel schedule

The ratio W_f/P_{s3} represents the fuel flow (W_f) relative to the compressor exit pressure (P_{s3}) and is a simple yet effective parameter used for fuel control during start. This

ratio normalizes pressure variations under different environmental and operating conditions, providing a more consistent fuel delivery strategy and reducing the risk of temperature exceedance and surge due to over fueling. However, its main disadvantage is that it does not directly control engine acceleration and does not adequately capture dynamic responses; therefore, it is limited in optimizing start performance compared to more advanced control methods such as NDOT. **Figure 3.32** illustrates the constant W_f/P_{s3} lines used during acceleration above idle.

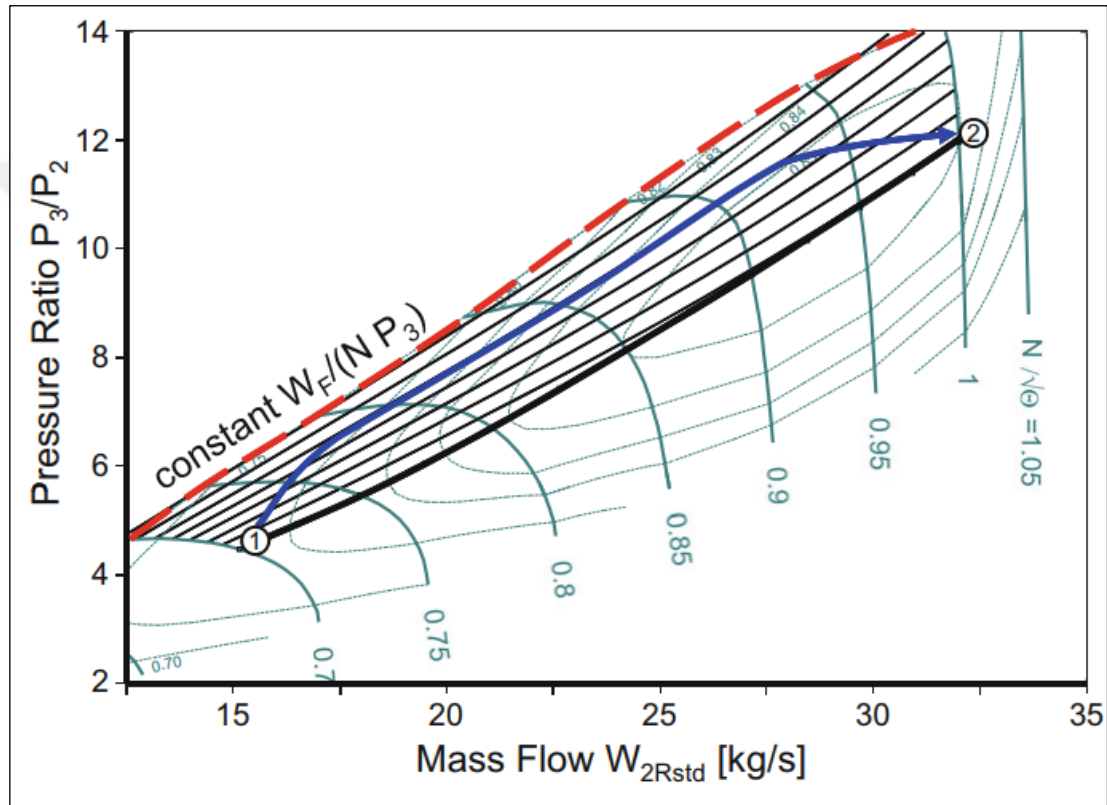


Figure 3.32: Constant W_f/P_{s3} lines on compressor map [2].

The primary reason for using an NDOT controller in modern gas turbine engines is to maintain engine acceleration within safe limits during start, thereby protecting temperature limits and reducing the risk of compressor surge. By regulating fuel flow according to a normalized acceleration rate, NDOT provides a consistent acceleration profile under varying environmental conditions and safely manages starter–turbine torque sharing. Due to these characteristics, NDOT control is an effective and reliable start control strategy preferred by FADEC systems. **Figure 3.33** illustrates constant

NDOT/ δ lines on the compressor map for above-idle acceleration. In this study, the NDOT controller is selected for the starting acceleration phase.

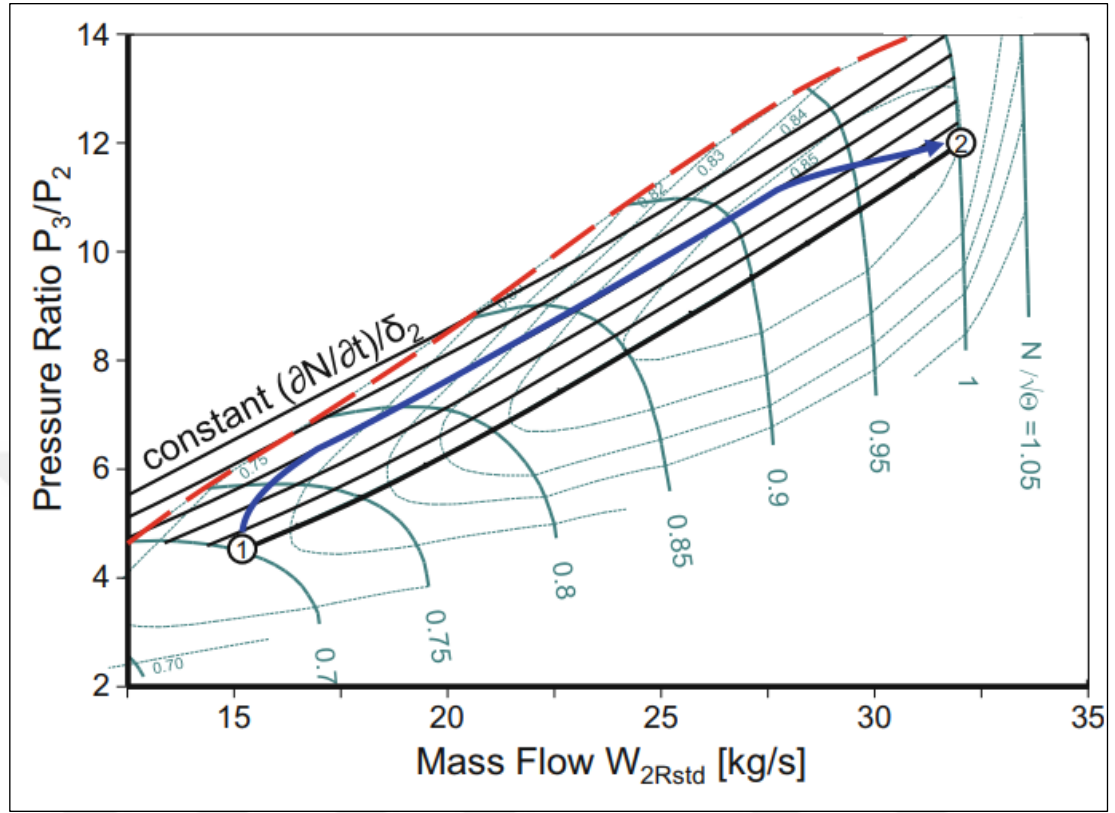


Figure 3.33: Constant NDOT/ δ lines on compressor map [2].

After the starting acceleration schedule is defined, the idle controller is designed. A typical speed PI controller is shown in **Figure 3.34**. The idle speed is selected as 75% of the design speed, meaning that the PI controller delivers fuel to bring the actual shaft speed to the idle speed of 10,713 rpm. During the tuning of the controller gains, attention is paid to ensure that the engine response is not too abrupt and that it smoothly settled at the idle speed.

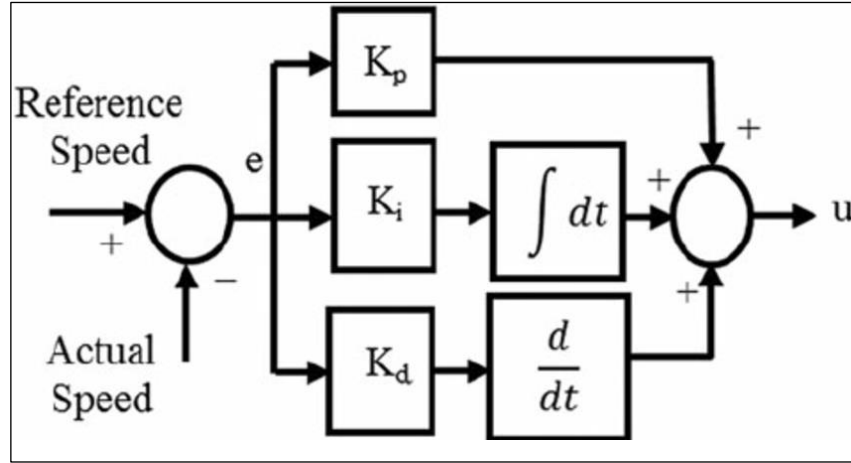


Figure 3.34: Typical speed PI controller

The starter typically cuts out between 40% and 60% of the shaft speed [28]. In this study, the starter cut-out speed is set at 60% of the shaft speed to reduce the turbine load during starting. All parameters controlled during the start and their respective control speed ranges are shown in **Figure 3.35**.

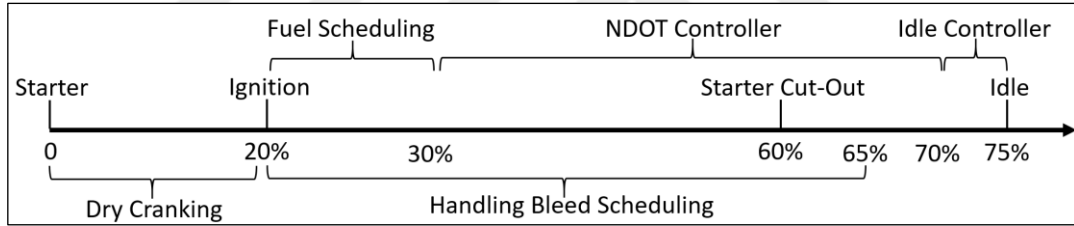


Figure 3.35: Starting control logic

3.3.2.4.5. Starting Limits

Gas turbine engines are constrained by aerodynamic, structural, and operational limits that are critical for safe and reliable operation. Among these, the most important include the compressor surge margin, the exhaust gas temperature (EGT) limit, and the allowable starting duration. In this study, a surge margin limit of 10% is selected to ensure the engine operates safely without approaching the surge line, which is consistent with typical design practices [29]. The EGT limit is set at 900 K to prevent thermal overstress of turbine components. The starting time is limited to 45 seconds at static sea level conditions under ISA, ensuring reliable ignition and acceleration. These limits serve as fundamental references for the design of fuel schedules, ignition

control, and other starting strategies. Together, they collectively ensure safe and efficient engine start and idle operation.



4. RESULTS

First, the steady-state turbojet engine model developed in NPSS is compared with the GasTurb results at both design and off-design operating points. Subsequently, the Simulink model prepared for transient analyses is validated by comparing its outputs with the transient results obtained from GasTurb. Finally, the starting analysis results, which constitute the main objective of this study, are presented.

4.1. Design Point Results

The station values and critical cycle parameters at the design point for the NPSS and GasTurb turbojet models are presented in **Table 4.1** and **4.2**. It can be seen from these tables that the error for all parameters remains below 0.055%.

Table 4.1: Station based results at design point

Station	Mass Flow [kg/s]		Temperature [K]		Pressure [kPa]	
	NPSS	GasTurb	NPSS	GasTurb	NPSS	GasTurb
1	31.68	31.68	288.15	288.15	101.33	101.33
2	31.68	31.68	288.15	288.15	100.31	100.31
3	31.68	31.68	630.62	630.42	1203.75	1203.74
31	28.19	28.19	630.62	630.42	1203.75	1203.74
4	28.86	28.86	1450	1450	1167.63	1167.63
41	30.44	30.44	1411.13	1411.2	1167.63	1167.63
49	30.44	30.44	1113.88	1113.5	367.21	367.37
5	32.02	32.02	1091.74	1091.37	367.21	367.37
6	32.02	32.02	1091.74	1091.37	359.87	360.03
8	32.02	32.02	1091.74	1091.37	359.87	360.03
Bleed	0.3168	0.3168	630.62	630.42	1203.75	1203.74

Table 4.2: Critical cycle parameters at design point

	NPSS	GasTurb	Error [%]
Fuel Flow [kg/s]	0.662	0.6619	0.0121
Fuel-to-Air Ratio	0.0211	0.0211	-0.0071
Mechanical Speed [rpm]	14284	14284	0
Net Thrust [kN]	26.09	26.09	0
Specific Fuel Consumption [g/(kN.s)]	25.379	25.376	0.0122
Turbine Pressure Ratio	3.1797	3.178	0.0547
Compressor Pressure Ratio	12	12	0
Turbine Specific Power	365.47	365.49	-0.0055
Compressor Specific Power	-351.14	-351.16	-0.0052

4.2. Off-Design Points Results

The three off-design cases analyzed are as follows.

1. SLS ISA+30°C without power extraction,
2. 500 kW of extracted power at SLS ISA,
3. 70% shaft speed at SLS ISA without power extraction.

The off-design results of these three cases are presented in **Table 4.3**, **4.4** and **4.5**, respectively. When examining the results of these three cases, it is observed that the highest error occurs in the fuel flow of Case-3, with an error of 0.75%. This discrepancy may stem from differences in the thermodynamic property tables embedded in NPSS and GasTurb.

Table 4.3: Critical cycle parameters of case 1 (ISA+30)

	NPSS	GasTurb	Error [%]
Net Thrust [kN]	22.94	22.88	0.2616
Fuel Flow [kg/s]	0.60729	0.60573	0.2569
Compressor Pressure Ratio	10.8538	10.825	0.2653
Turbine Pressure Ratio	3.1689	3.165	0.1231
Burner Pressure Ratio	0.9693	0.9693	0
Turbine Inlet Temperature [K]	1508.68	1502.83	0.3878
Inlet Air Flow [kg/s]	28.042	28.041	0.0036

Table 4.4: Critical cycle parameters of case 2 (500 kW)

	NPSS	GasTurb	Error [%]
Net Thrust [kN]	27.57	27.47	0.3627
Fuel Flow [kg/s]	0.7591	0.7548	0.5665
Compressor Pressure Ratio	12.451	12.408	0.3454
Turbine Pressure Ratio	3.162	3.158	0.1265
Burner Pressure Ratio	0.9717	0.9717	0
Turbine Inlet Temperature [K]	1561.31	1554.76	0.4195
Inlet Air Flow [kg/s]	31.648	31.65	-0.0063

Table 4.5: Critical cycle parameters of case 3 (Speed of 70%)

	NPSS	GasTurb	Error [%]
Net Thrust [kN]	5.41	5.38	0.5545
Fuel Flow [kg/s]	0.14481	0.14372	0.7527
Compressor Pressure Ratio	4.491	4.459	0.7125
Turbine Pressure Ratio	2.974	2.965	0.3026
Burner Pressure Ratio	0.963	0.963	0
Turbine Inlet Temperature [K]	900.2	896.86	0.371
Inlet Air Flow [kg/s]	15.0866	15.07	0.11

4.3. Transient Analysis Results

The transient analysis results obtained using the transient schedule described in 3.3.1 are presented in **Figure 4.1**. As observed from the results, the outcomes of the two models are very close to each other. Minor differences exist due to the different gains of the PI controllers used in Simulink and GasTurb. However, as optimizing the controller gains is not the primary focus of this study, no extensive effort is devoted to this optimization.

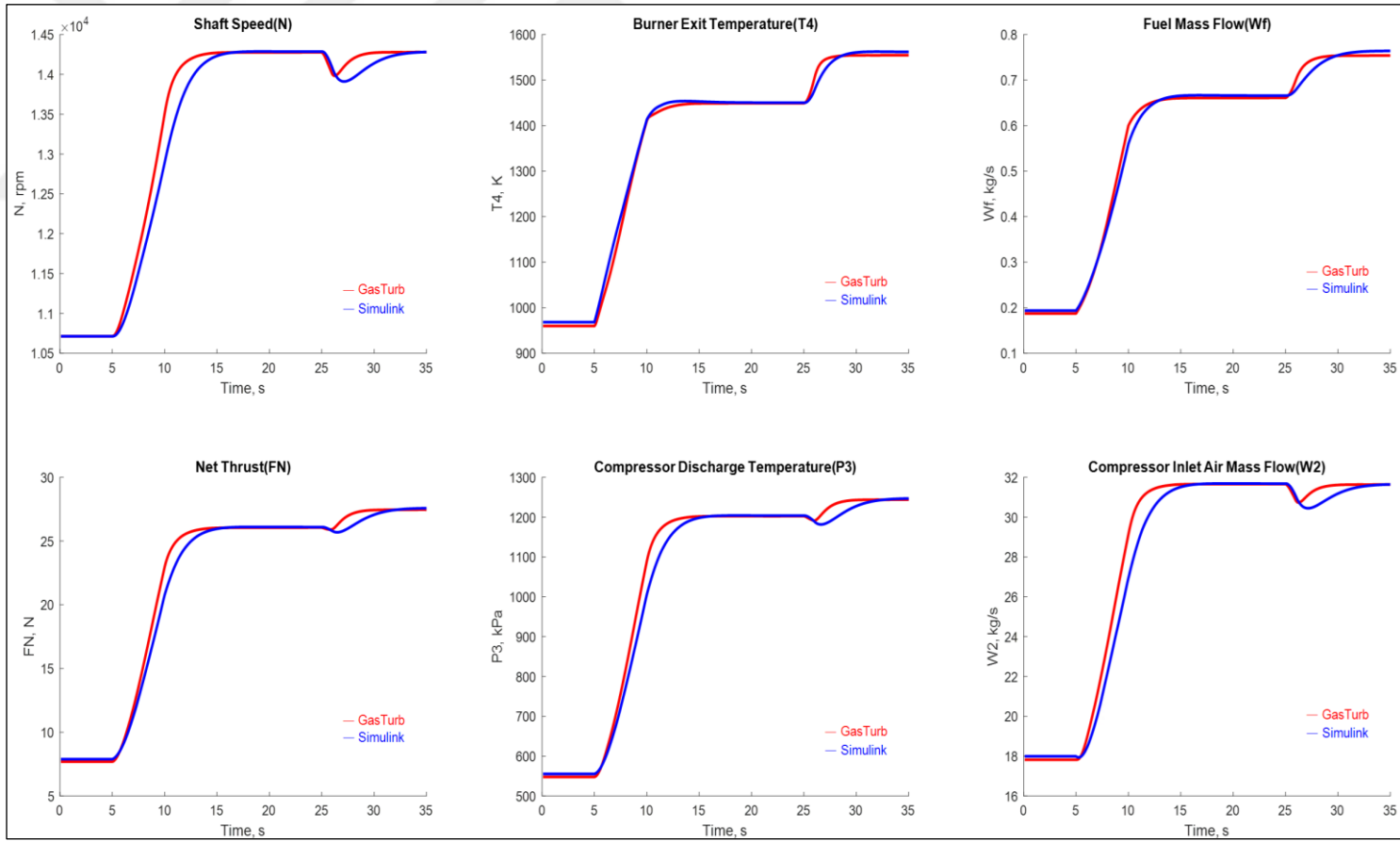


Figure 4.1: Transient analysis results comparison between simulink and GasTurb

4.4. Initial Starting Analysis Results

The operating line on the compressor map for the starting analysis performed according to the starting fuel control described in 3.3.2.4.4 is shown in **Figure 4.2**.

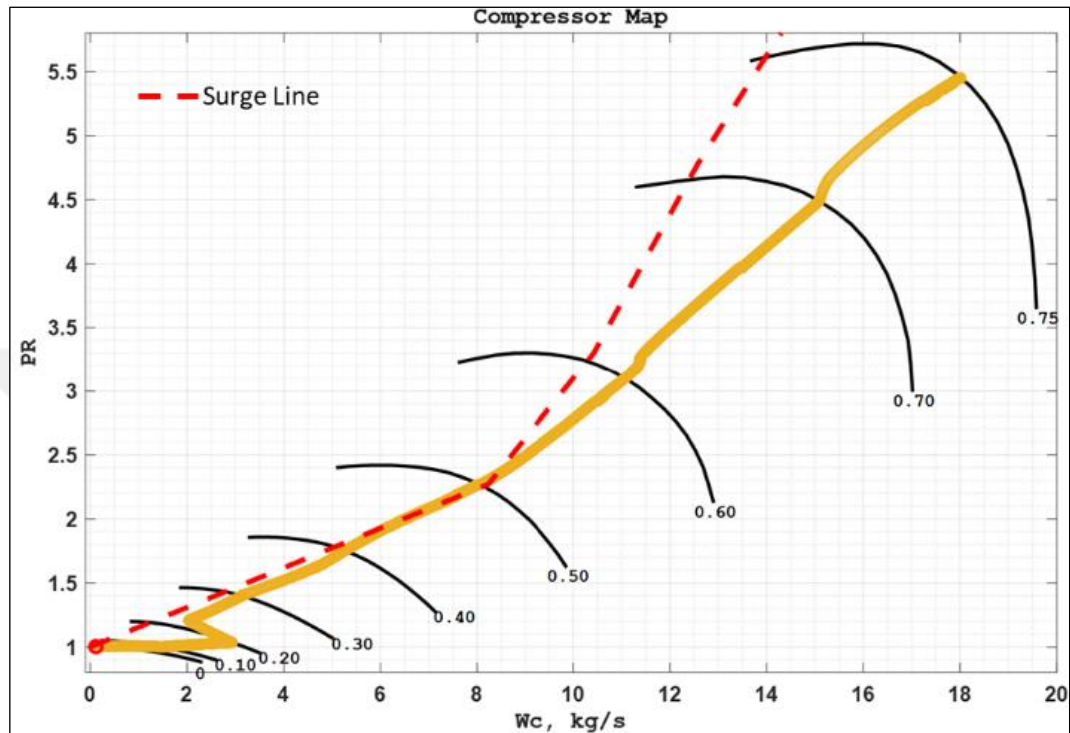


Figure 4.2: Starting operating line on the compressor map

In this initial starting analysis, no handling bleed is used, and a starter with approximately 100 kW of power is employed. As observed from the results, the compressor enters surge at around 40–50% shaft speed. This indicates that a starting handling bleed is required for this engine.

4.5. Starting Analysis Results with Variable and Constant Handling Bleed Schedules

The starting analysis results obtained using fixed and variable 20% handling bleed schedules are presented in **Figure 4.3**. The results clearly indicate that, when a variable surge bleed is applied while maintaining an adequate surge margin, the engine start duration is reduced and turbine inlet temperatures decreased. Consequently, a variable handling bleed schedule is employed to optimize engine starting performance.

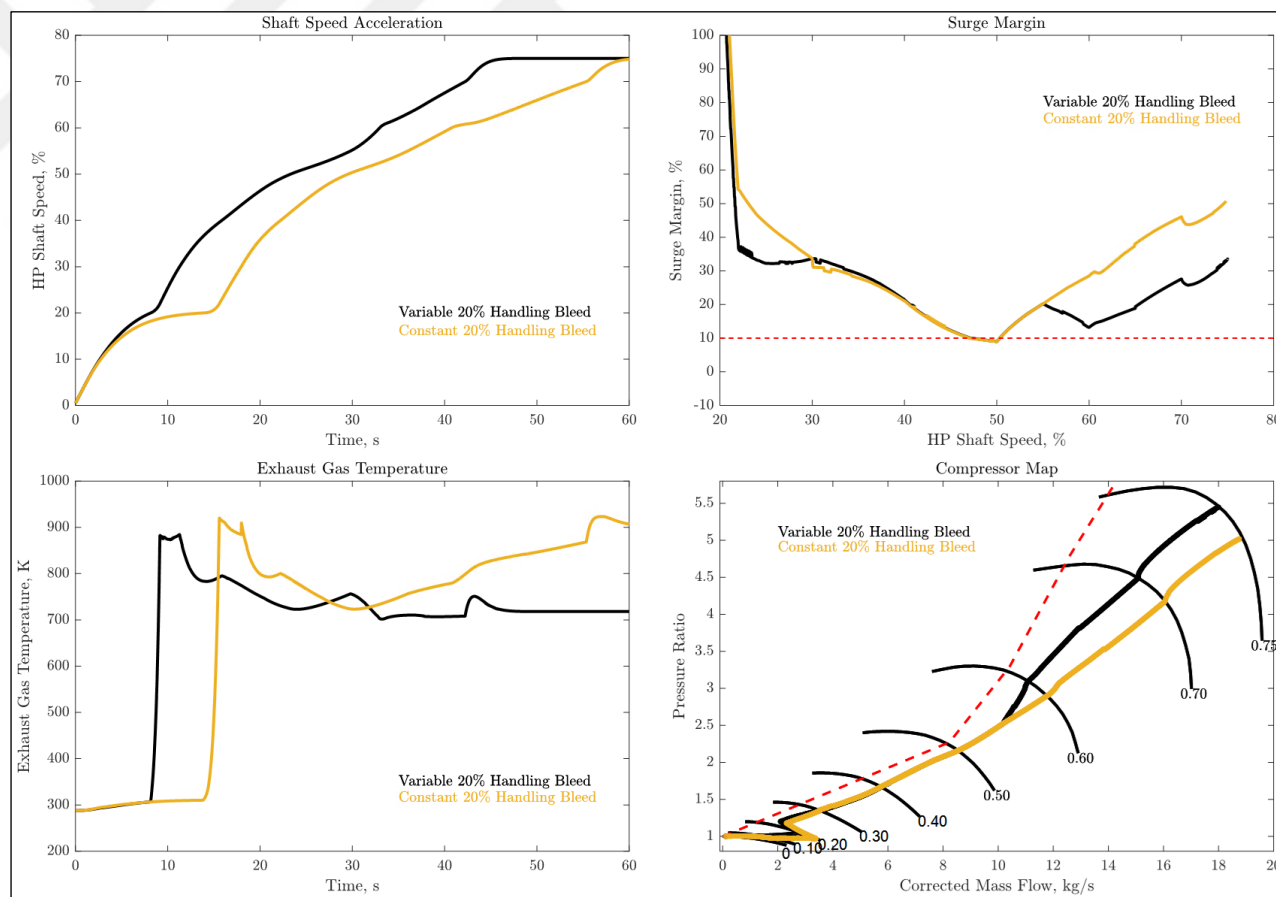


Figure 4.3: Starting analysis results with variable and constant handling bleed schedules

4.6. Starting Analysis Results with Different Starter Torques and Different Handling Bleed Schedules

As mentioned in 3.3.2.4.2, the minimum starter power required by the compressor during ignition is in the range of 90–100 kW. Accordingly, four different starter powers are selected for use in the starting analyses, as shown in **Figure 4.4**.

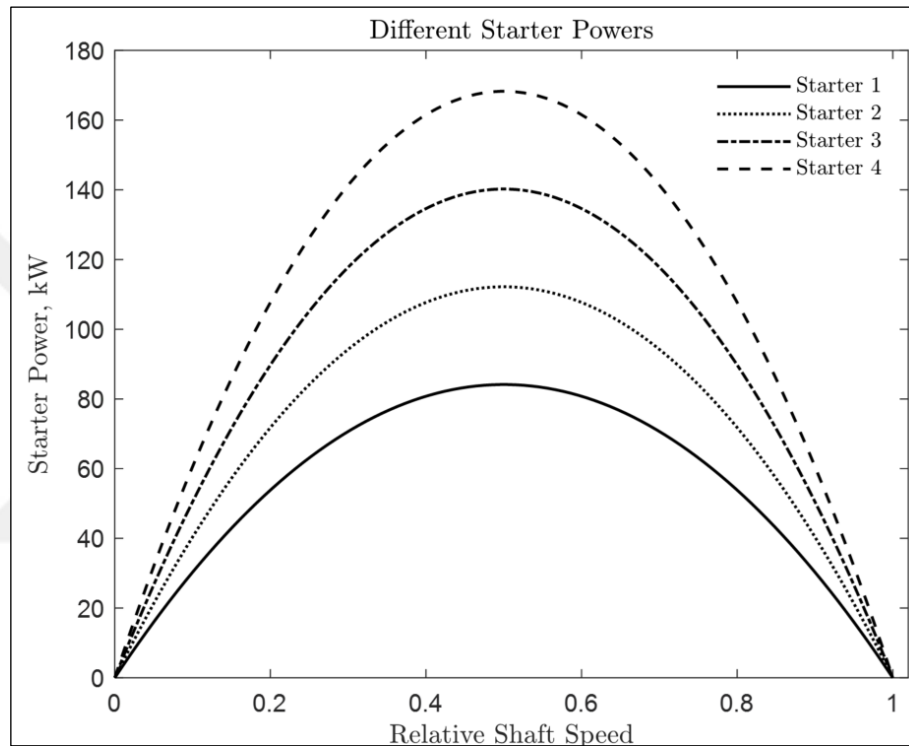


Figure 4.4: Different starter powers

The torque–rpm corresponding to these starter powers is presented in **Figure 4.5**.

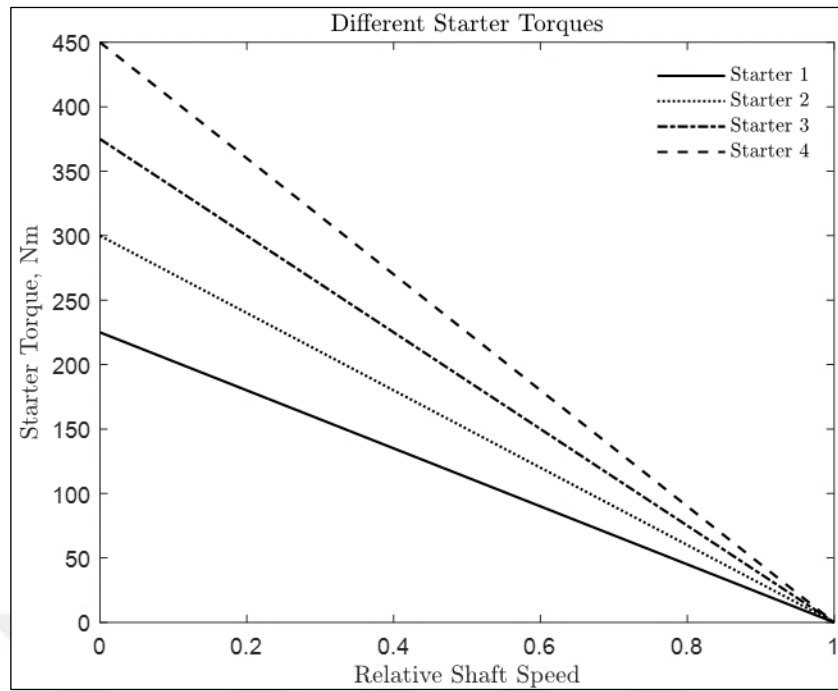


Figure 4.5: Different starter torque

The four different handling bleed schedules used in the starting analyses are shown in **Figure 4.6**.

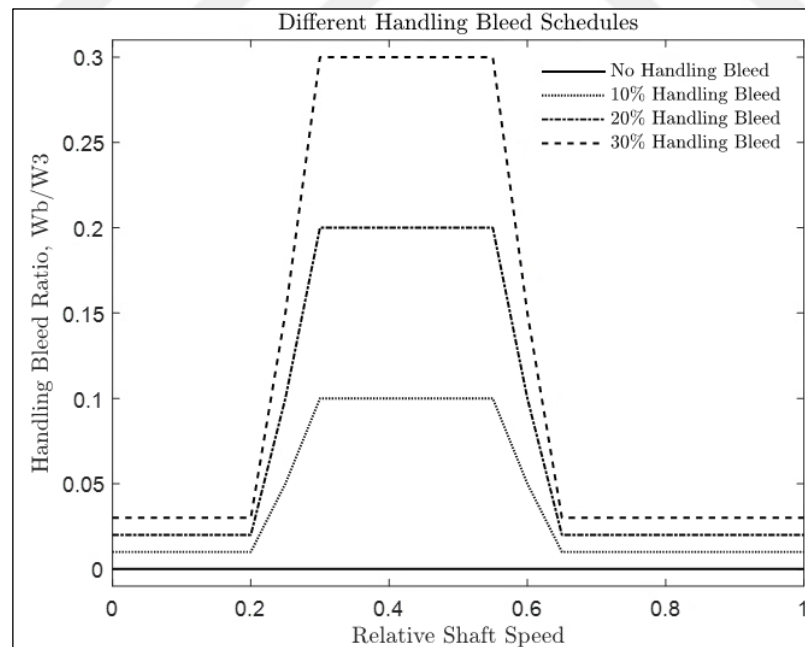


Figure 4.6: Different handling bleed schedules

Starting analysis results for four distinct starter power levels are presented in **Figure 4.7, 4.8, 4.9 and 4.10**.

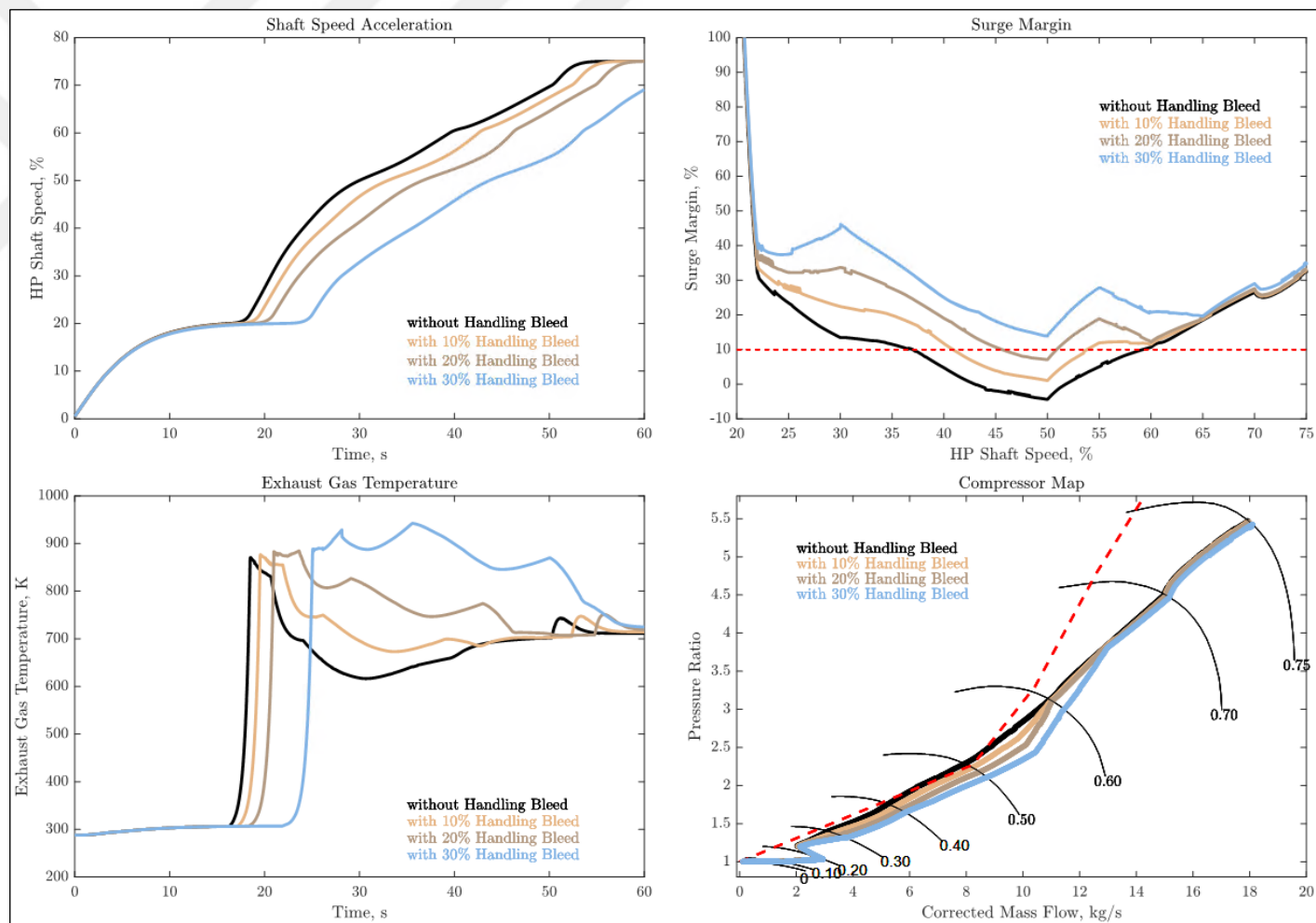


Figure 4.7: Starting analysis results for different handling bleed schedules with starter 1

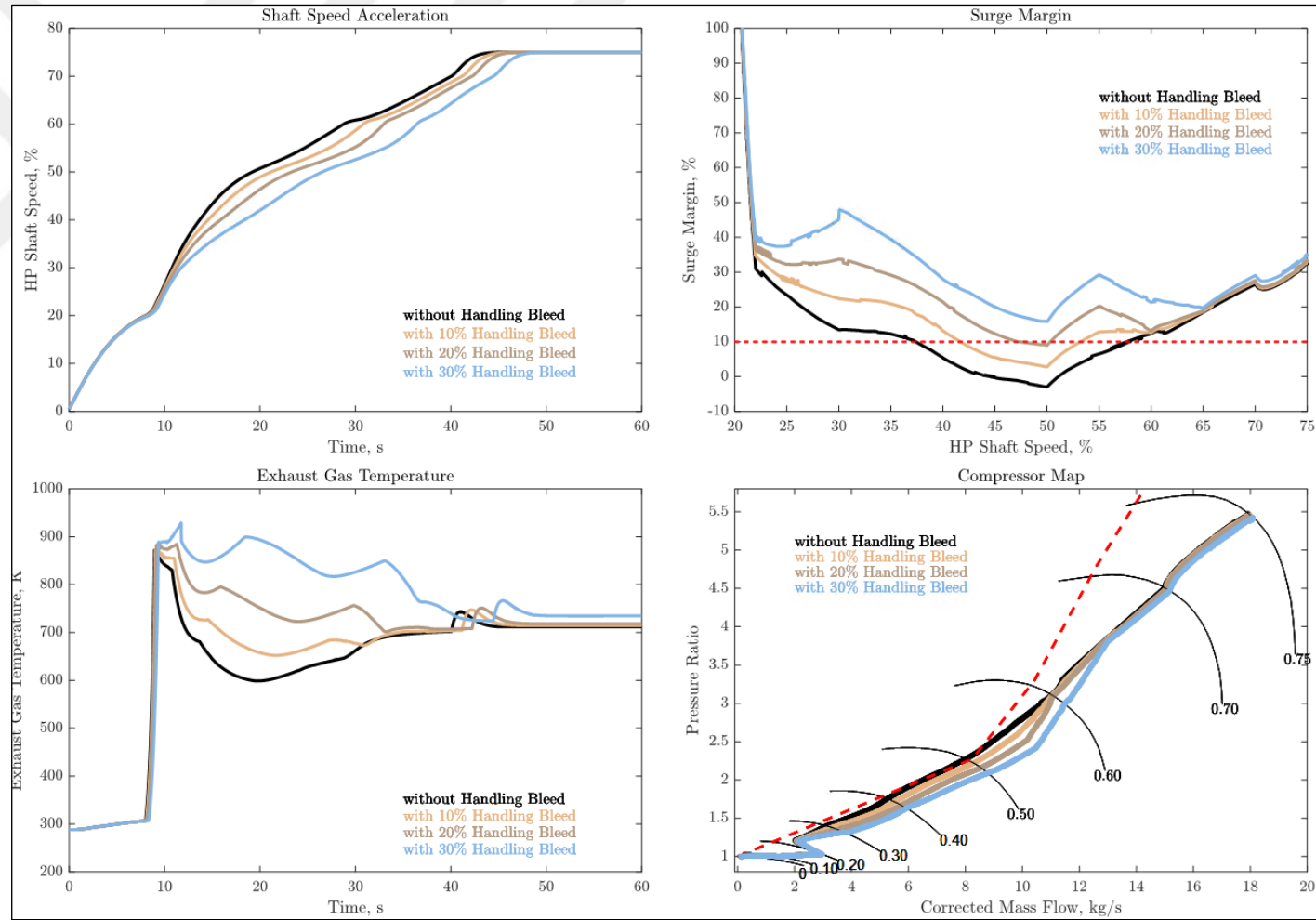


Figure 4.8: Starting analysis results for different handling bleed schedules with starter 2

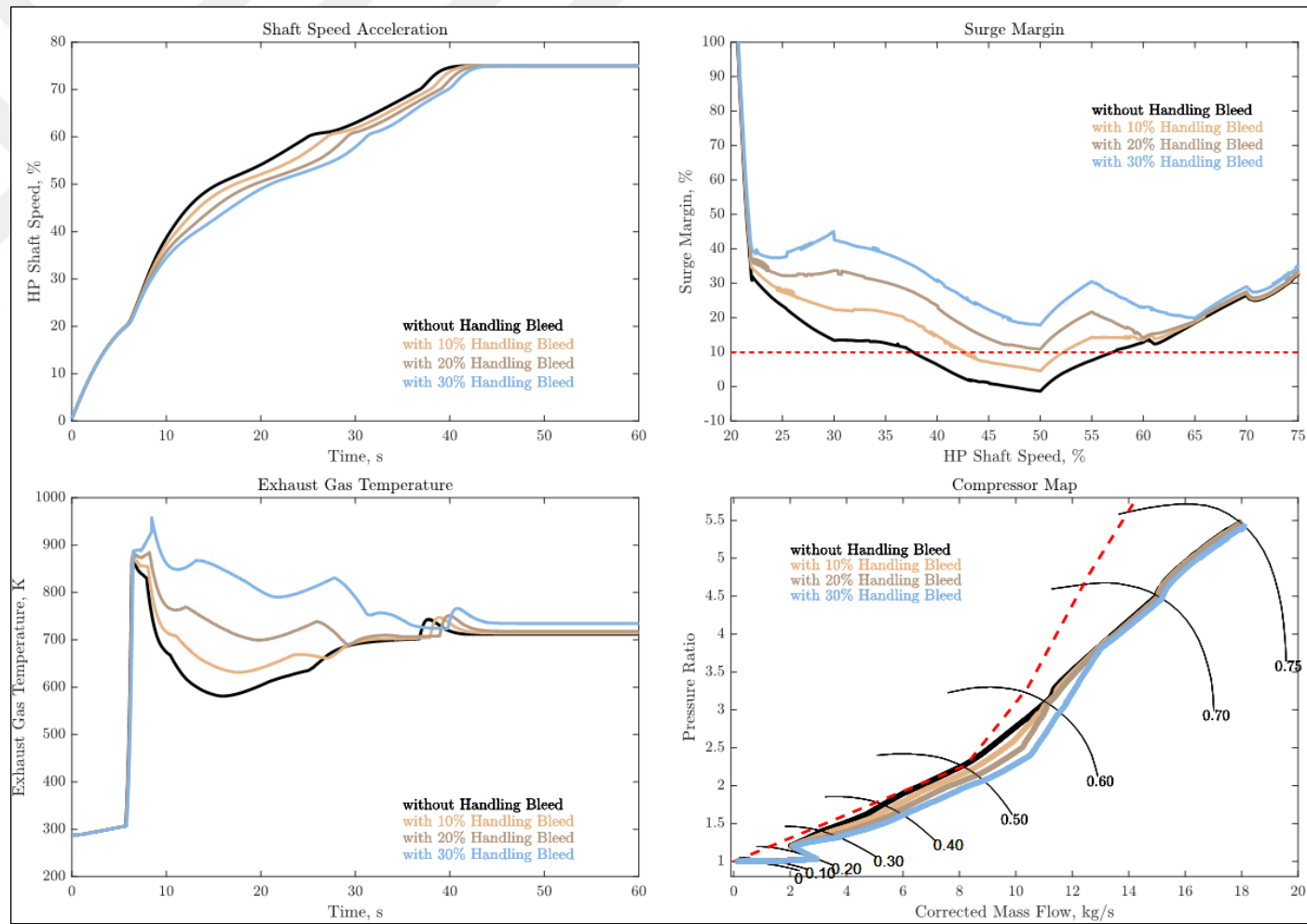


Figure 4.9: Starting analysis results for different handling bleed schedules with starter 3

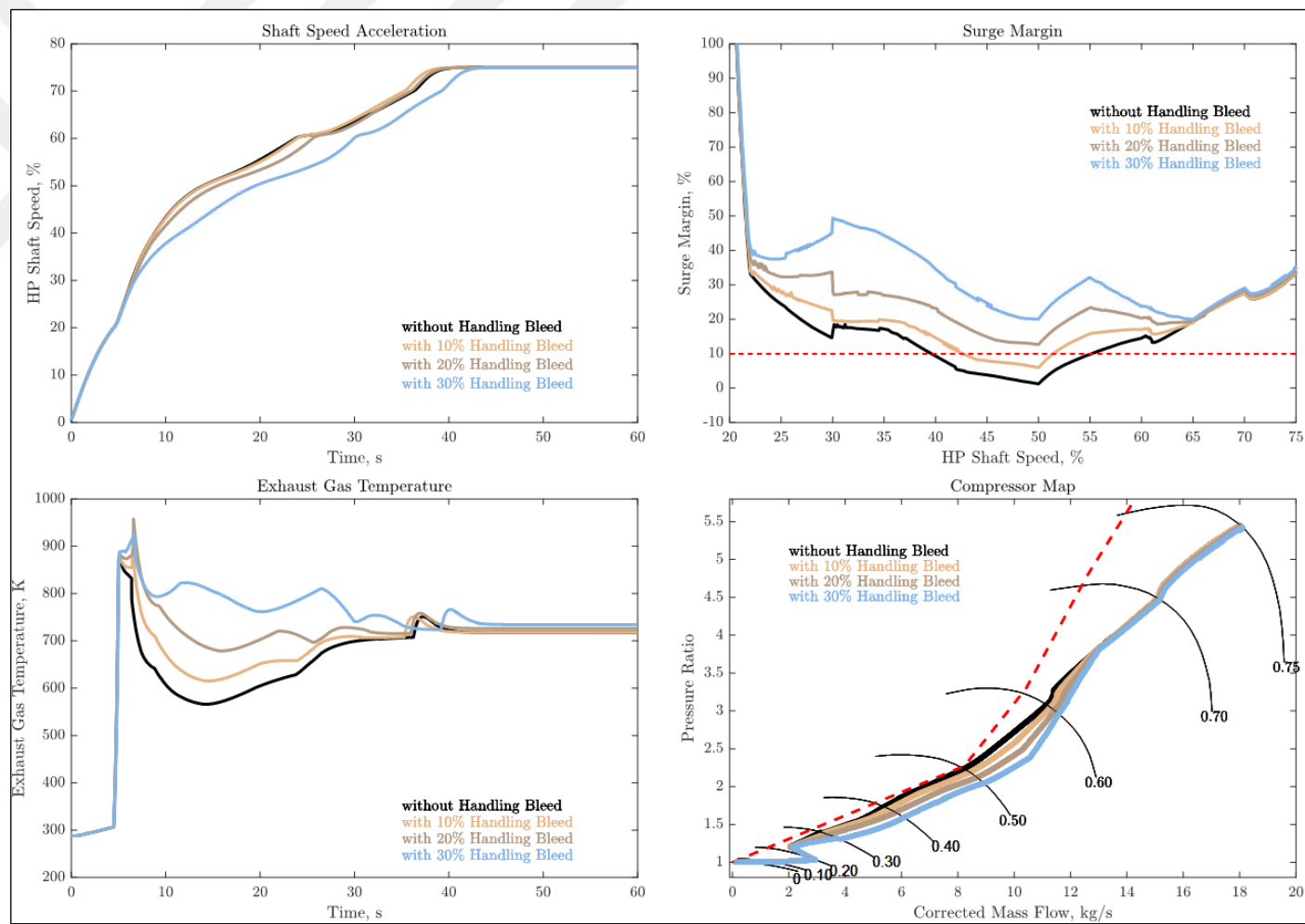


Figure 4.10: Starting analysis results for different handling bleed schedules with starter 4

As shown in **Figure 4.7**, the starting time (time to reach idle) exceeds 50 seconds for all bleed schedules. Considering that these analyses are performed at SLS ISA conditions, it is anticipated that starting times under cold day, hot day, and high-altitude conditions could exceed 90 seconds. This duration is longer than the starting requirements for many engines. Ensuring a starting time of less than 45 seconds at SLS ISA is expected to improve starting times under other conditions.

As can be seen in **Figure 4.8**, the only case that satisfies the 10% surge margin limit is when a 30% handling bleed is applied. In this case, the EGT rises above 900 K immediately after ignition. Additionally, using this handling bleed schedule results in a starting time exceeding 45 seconds.

Figure 4.9 shows two handling bleed schedules that satisfy the 10% surge margin limit. In all cases, the starting time remains below 45 seconds. However, when a 30% handling bleed is used, the EGT limit of 900 K is again exceeded immediately after ignition. In this context, Starter 3 combined with a 20% handling bleed schedule satisfies all limits and requirements.

As shown in **Figure 4.10**, due to the high starter power, the starting times are below 40 seconds in almost all cases. However, only the cases with 20% and 30% handling bleed schedules meet the 10% surge margin limit. Examining the EGT trends indicates that both of these handling bleed schedules result in temperatures exceeding 900 K.

The results indicate that an increase in starter power leads to a significant reduction in starting time. With higher starter power, the shaft accelerates more rapidly, thereby reducing the time spent in the low-speed operating region. Increasing the handling bleed fraction reduces the compressor load and improves the surge margin at low rotational speeds. However, a higher handling bleed level also decreases the airflow entering the combustor, which results in an increased fuel–air ratio immediately after ignition. Consequently, the turbine inlet temperature, and therefore the EGT, rises rapidly, leading to the exceedance of temperature limits at certain bleed levels. These findings demonstrate that starting time, surge margin, and thermal limits are strongly coupled parameters, and that engine start performance requires a combined evaluation of starter power and handling bleed level.

5. CONCLUSION AND FUTURE WORK

5.1. Conclusion

The simulation results revealed that increasing the starter power provided a modest improvement in compressor surge behavior by shifting the operating point further away from the surge line. However, the overall surge margin remained critically low in most scenarios. A secondary effect of higher starter power is a noticeable reduction in the time required for the engine to reach idle, indicating improved acceleration characteristics during the starting phase.

Furthermore, applying a higher bleed mass flow rate from the compressor outlet effectively enhanced the surge margin. Nevertheless, this approach reduced the airflow delivered to the turbine, thereby necessitating a higher turbine inlet temperature (TIT) to sustain the required power output.

Among the sixteen cases studied, six combinations maintain the compressor surge margin above the 10% safety threshold throughout the start sequence. However, five of these six cases exceed the 900 K starting EGT limit. Consequently, a final selection of a starter and handling bleed schedule is made, balancing surge protection, thermal limits, starter weight considerations and starting time requirements. This outcome highlights the necessity of achieving an optimal balance between starter power and handling bleed management strategies to ensure safe and reliable engine starting performance.

5.2. Future Work

Future work will extend the present study to multi-spool turbofan engines, focusing on two- and three-spool configurations. The dynamic interaction among the low-, intermediate-, and high-pressure spools during engine start is expected to influence compressor matching and surge margin characteristics; therefore, future studies will model these coupled spool dynamics to evaluate the effects of starter power distribution and inter-stage bleed air management on starting stability and performance. In addition, the proposed methodology will be applied to turbofan

engines with different bypass ratios to investigate fan–core interactions during the starting phase and their impact on start reliability, acceleration time, and turbine inlet temperature behavior.



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BIOGRAPHY

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PUBLICATIONS AND PRESENTATIONS FROM THE THESIS

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